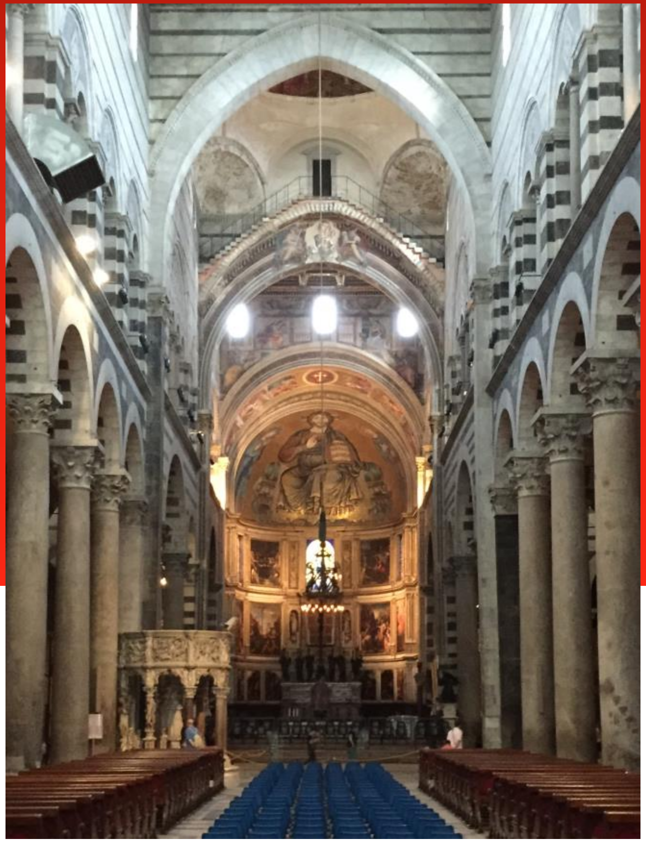
The Principle of Relativity



Tim Frost | ITSF 2019

Einstein or Galileo?

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- Galileo – naturally!
- Aside: Galileo should be our first honorary Time Lord
- "101 Things to do during a Dull Sermon":
    1. **Invent the next generation of Primary Reference Clock**
- Pendulum clocks became the earth's most accurate timekeepers for almost 300 years!

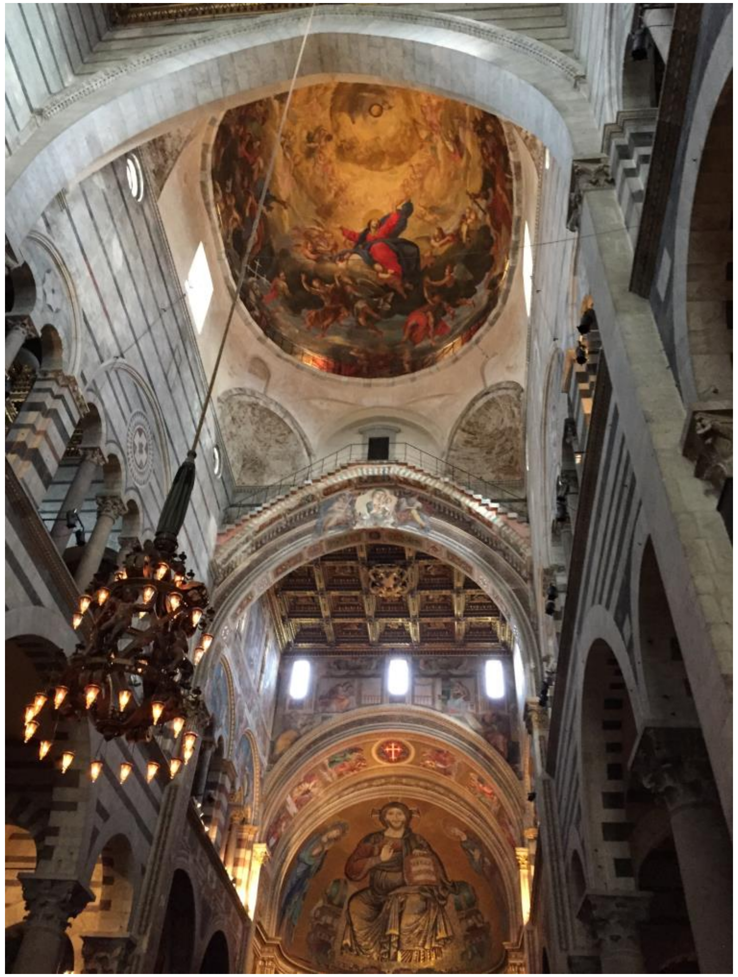
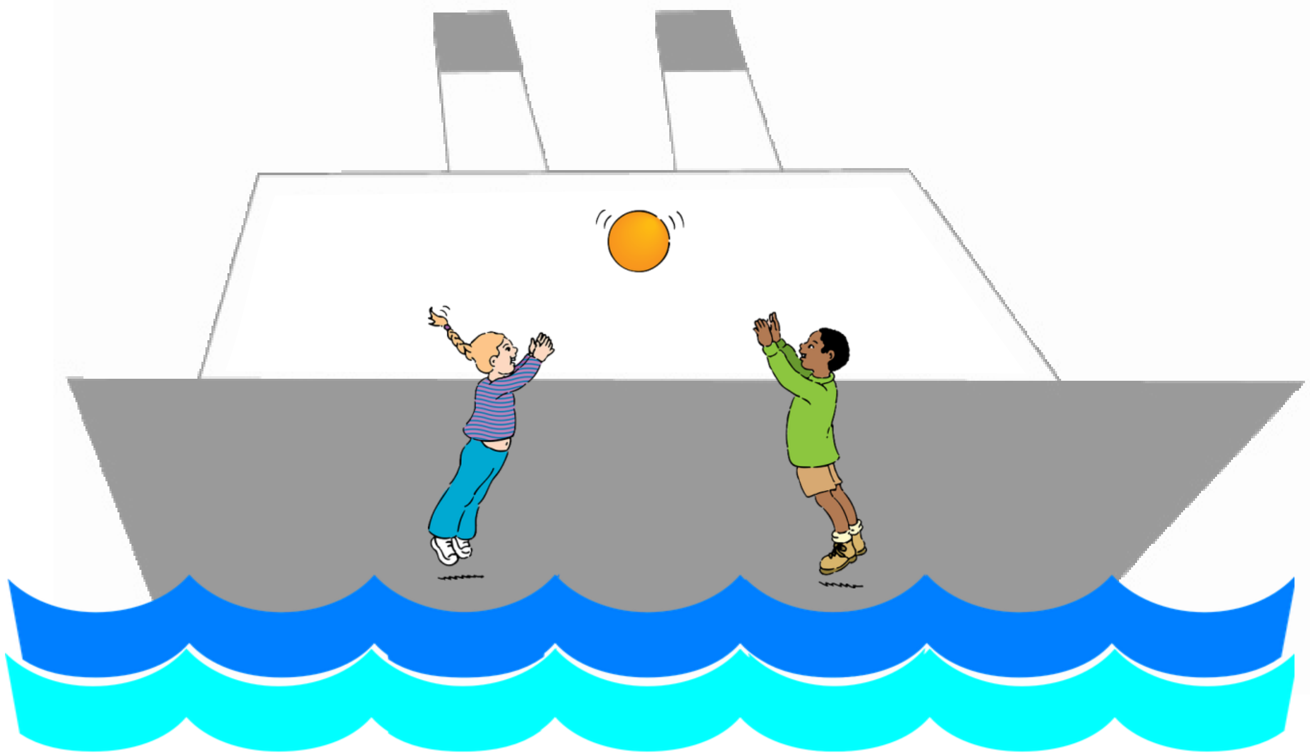


Photo: Cattedrale di Pisa

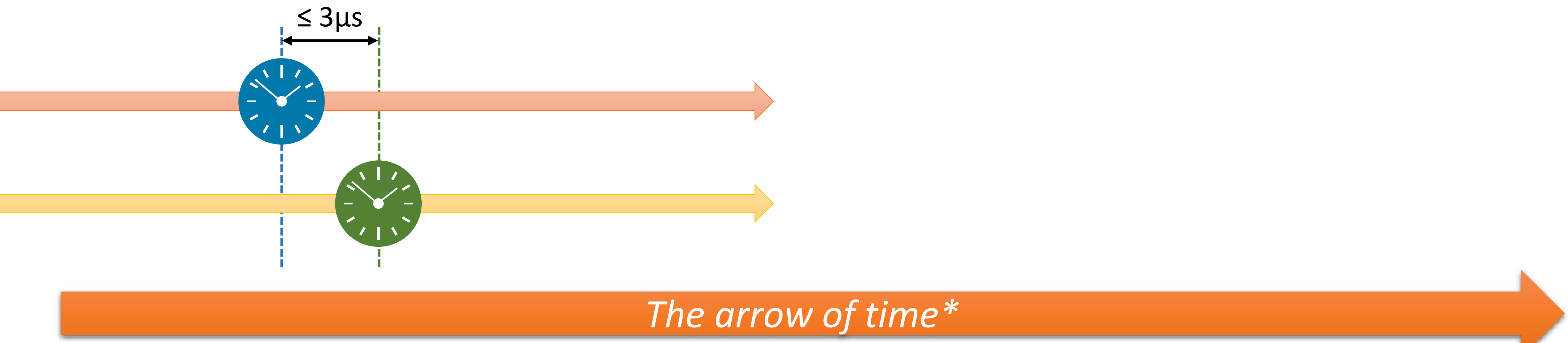
Galileo's Principle of Relativity

- "The laws of motion are the same in all inertial frames"
- Example:
  In a ship travelling at constant velocity on a smooth sea, an observer below deck would be unable to tell if the ship was moving or stationary
- This means someone on the ship throwing a ball to someone else would observe the same motion of the ball as though they were stationary on land



What does this mean for us?

- In most mobile cellular radio standards, the time accuracy requirements are relative
- Example 1: **Cell Phase Synchronization Accuracy** for TDD systems:
    - *“The maximum absolute deviation in frame start times between any pair of cells on the same frequency that have overlapping coverage areas shall be ≤ 3µs.”*
- Example 2: **Time Alignment Error (TAE)** for intra-band carrier aggregation:
    - *“The largest timing difference between any two signals shall not exceed 260ns”*



* the “inertial frame”

So why do we use absolute time?

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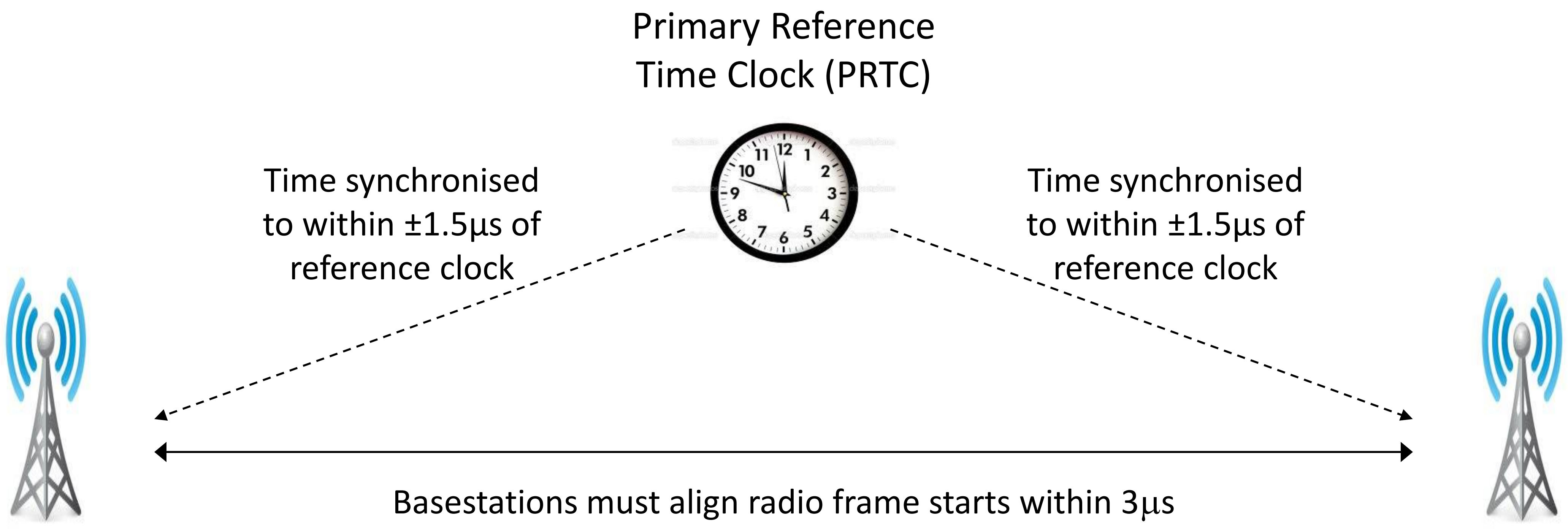
- We don’t: there is no such thing as “absolute time”
- All we can do is count regular events – such as Galileo’s pendulum swings, or astronomical events (days, months, years)
- “Common time” requires everyone to start counting at the same point, or “epoch”, and count at the same rate
- Example: a calendar counts days, months and years from a known starting point
  - Different calendars have different epochs
  - Epoch for the Gregorian calendar is the birth of Christ
  - Epoch for the Islamic calendar is the Hijra
- All “common time” is relative to the chosen epoch and counting rate

Common time reference in mobile radio

- Common time reference is used as a convenience
    - It ensures the two basestations are in the same “inertial reference plane”
    - It provides a measurement point to verify compliance
    - Relative time error goal is guaranteed provided accuracy requirements are met



Relative time accuracy requirements

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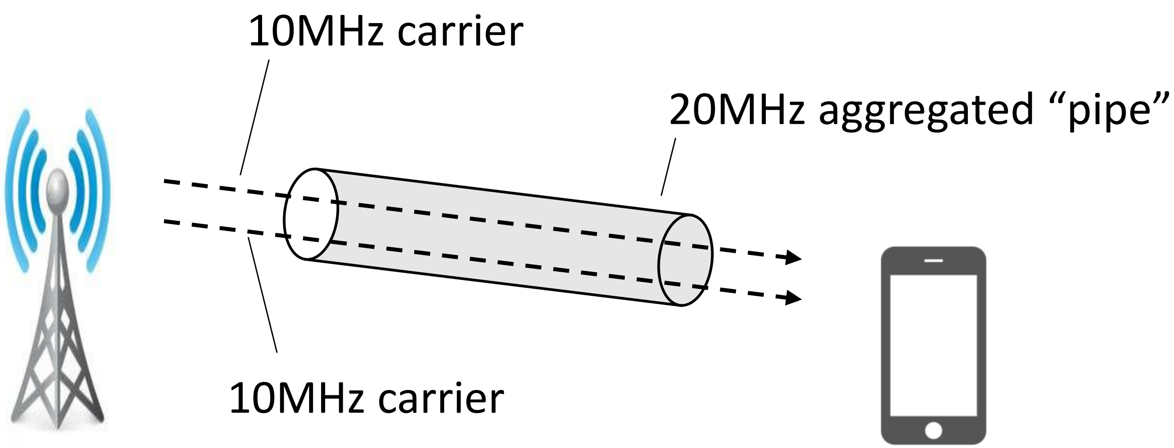
- In previous mobile generations (e.g. 3G WCDMA, 4G LTE) most operators deployed FDD
  - No time synchronization requirements
- Some TDD deployments *(notably China, some other countries)*
  - **CPSA requirement of 3µs** met by using a common time reference
- For 5G NR, most deployments will be TDD
  - **CPSA** is still **3µs** for 5G NR
  - TAE requirements also valid for Carrier Aggregation
    - **Inter-band CA** – TAE requirement is **3µs**
    - **Intra-band CA (non-contiguous)** – TAE requirement is **3µs**
    - **Intra-band CA (contiguous)** – TAE requirement is **260ns** or **130ns** (depending on frequency band)
- It is much harder to meet 260ns or 130ns using a centrally-located common reference clock

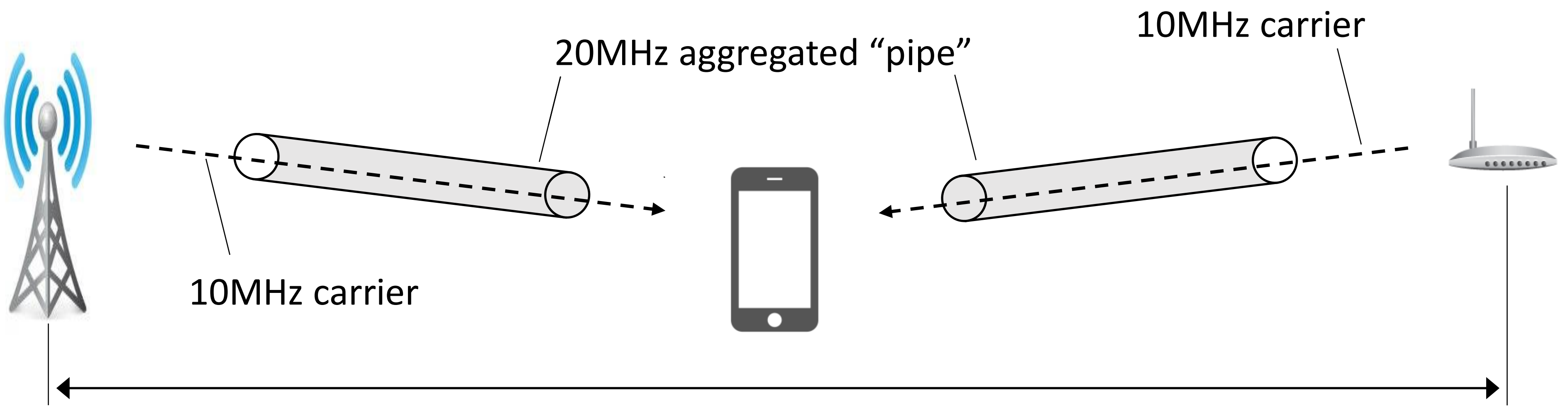
What is Carrier Aggregation?

- Carrier Aggregation bonds together two small carriers to make one big carrier
  - Radio frames must be aligned to within 260ns
  - Normally transmitted from same antenna, so not a network synchronisation problem



What is Carrier Aggregation?

- Carrier Aggregation bonds together two small carriers to make one big carrier
  - Radio frames must be aligned to within 260ns *(intra-band, contiguous CA)*
  - Normally transmitted from same antenna, so not a network synchronisation problem
- Inter-site carrier aggregation
  - Transmit second carrier from another basestation or small cell
  - Now there is a network synchronisation requirement of 260ns



Basestations must align radio frame starts within 260ns

Cluster Location

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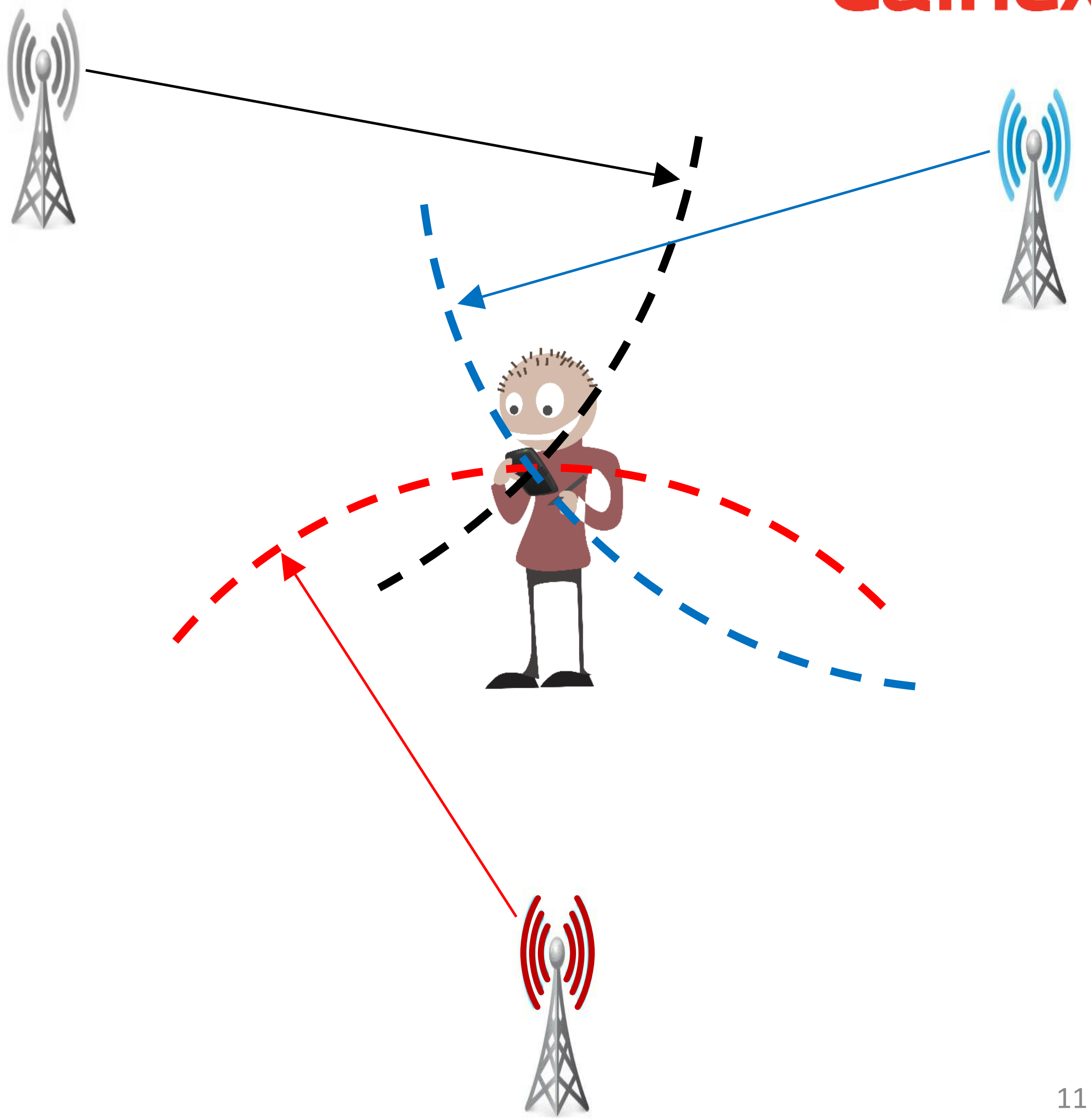
- Important point: Carrier Aggregation is only useful for overlapping coverage
  - Don’t need to synchronise every basestation in a network to within 260ns!
  - For intra-band carrier aggregation, only “collocated deployment” is applied
    - Term isn’t defined, but generally understood to mean “on the same rooftop” or “in the same building”
- So the requirement only applies between very closely located antennas
  - Small network in between, possibly no more than one or two switches

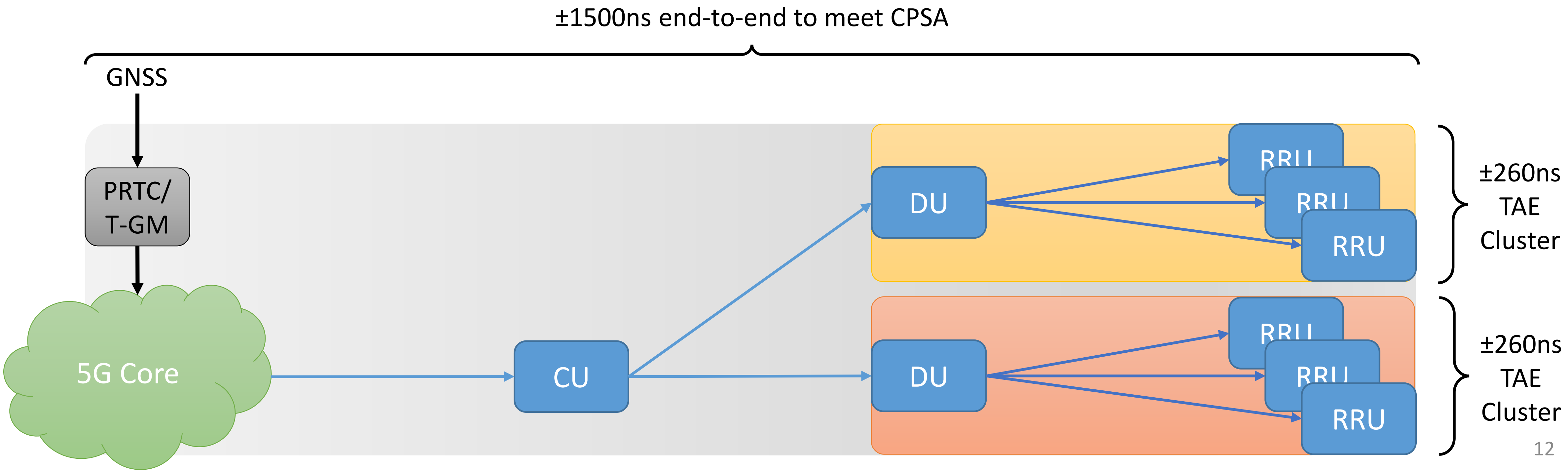
Positioning

- Emergency calls require position of caller to be determined to within 50m
- Normally uses the GNSS receiver in your phone to determine position
  - Position not always available indoors
- Observed Time Difference of Arrival (OTDOA)
  - Calculates position based on time of arrival of signals from three different basestations
  - Requires the basestations to be accurately synchronised in time to within approx. 100ns
  - For indoor location, basestations might be close together, e.g. small cells or radio units



Frontal Architectures

- Basestations for NR are exploded into three parts
  - Central Unit (CU), Distributed Unit (DU) and Remote Radio Unit (RRU)
- Carrier Aggregation and OTDOA protocols run in the DU
  - This permits “sync clusters” of very tightly synchronised elements



What is Relative Time Error?

- Definition of time error *(from G.810)*:

$$TE(t) = T_{\text{meas}}(t) - T_{\text{ref}}(t)$$

Time error

Time at measured clock

Time at reference clock

- Relative time error between timing signals A and B *(from G.8260)*:

$$TE_{\text{R}}(t)_{\text{A,B}} = T_{\text{A}}(t) - T_{\text{B}}(t)$$

Relative time error between clocks A and B

Time at clock A

Time at clock B

- Or the difference of the time errors of A and B, measured against a common reference:

$$TE_{\text{R}}(t)_{\text{A,B}} = TE_{\text{R}}(t)_{\text{A,ref}} - TE_{\text{R}}(t)_{\text{B,ref}}$$

Relative time error between clocks A and B

Time error at clock A

Time error at clock B

Relative Time Error

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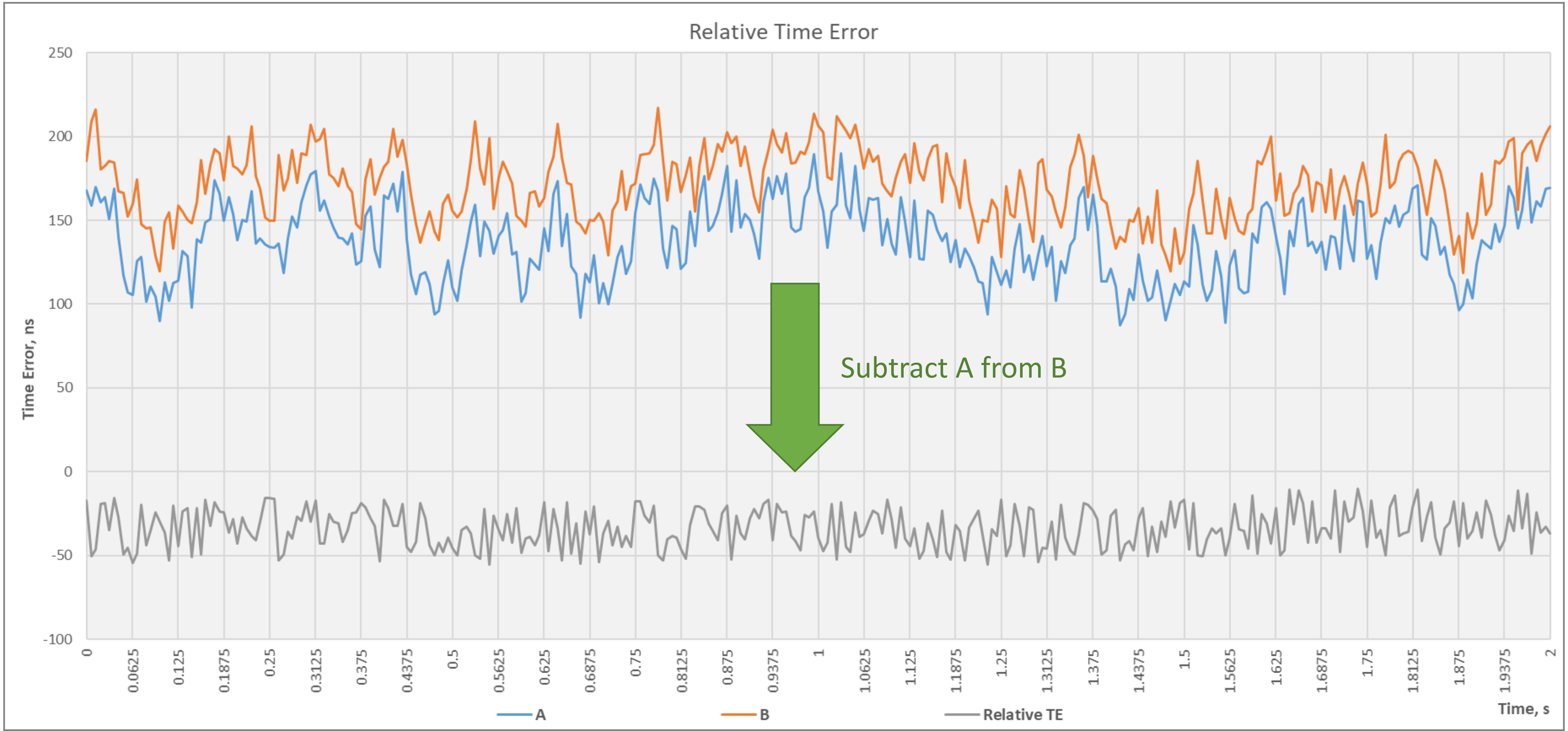
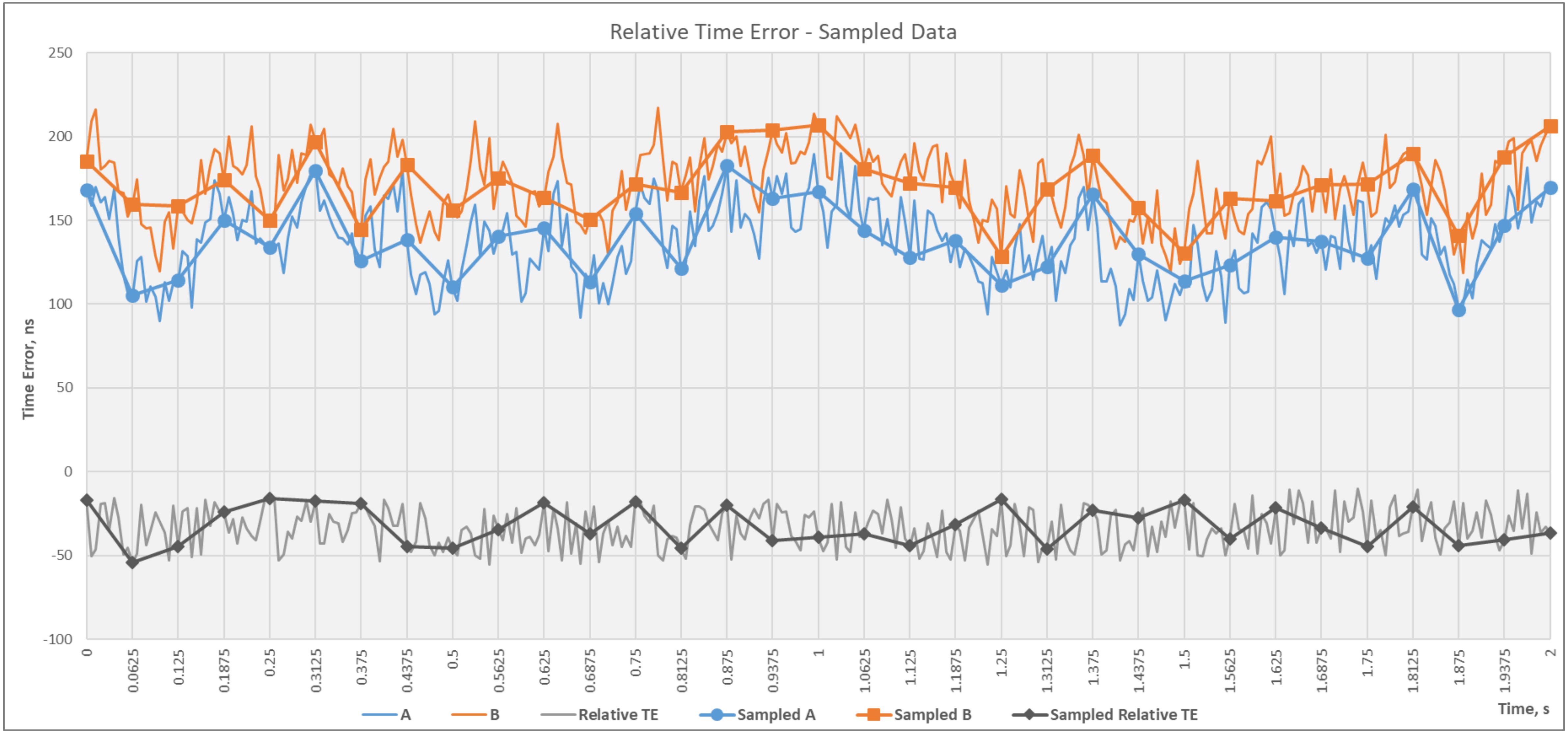
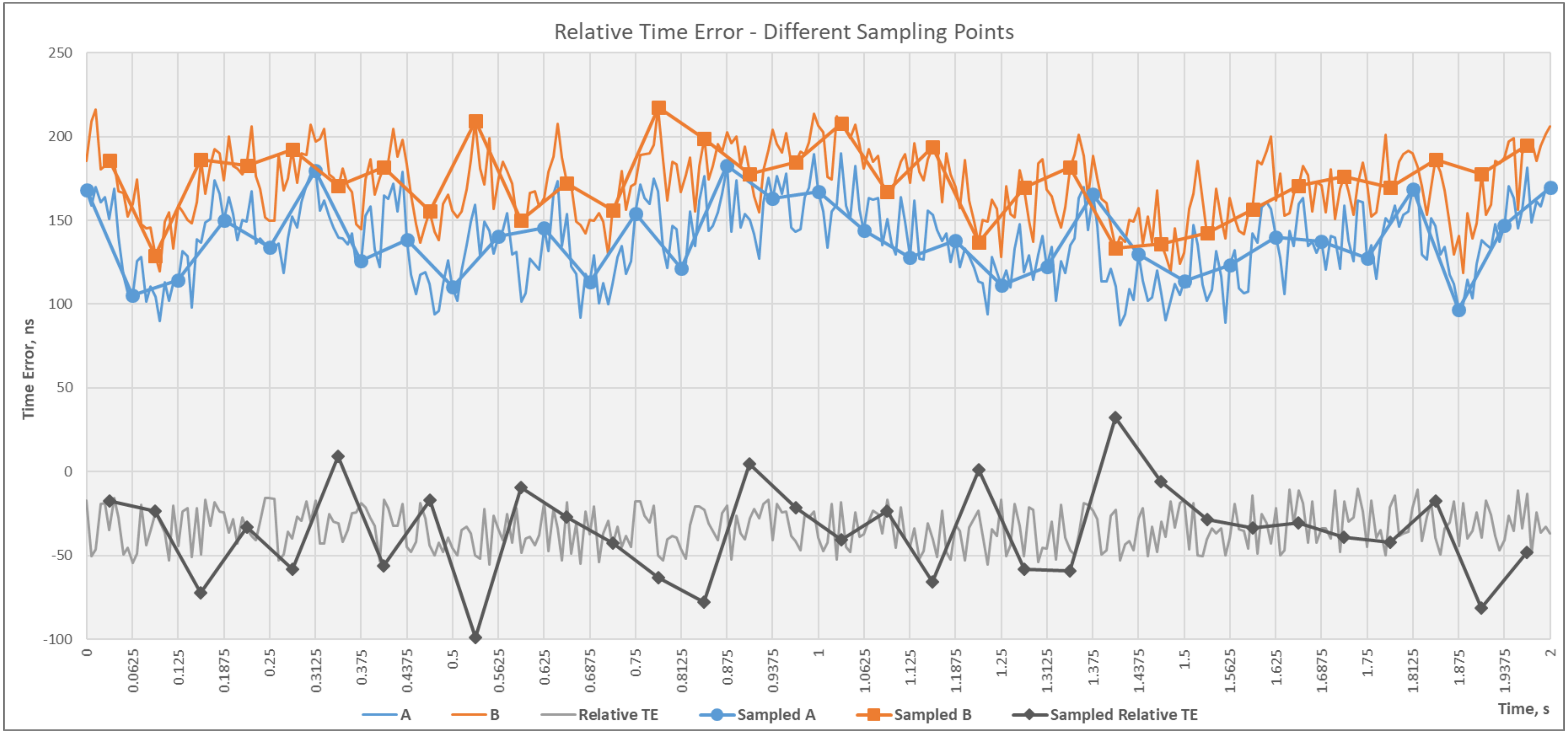


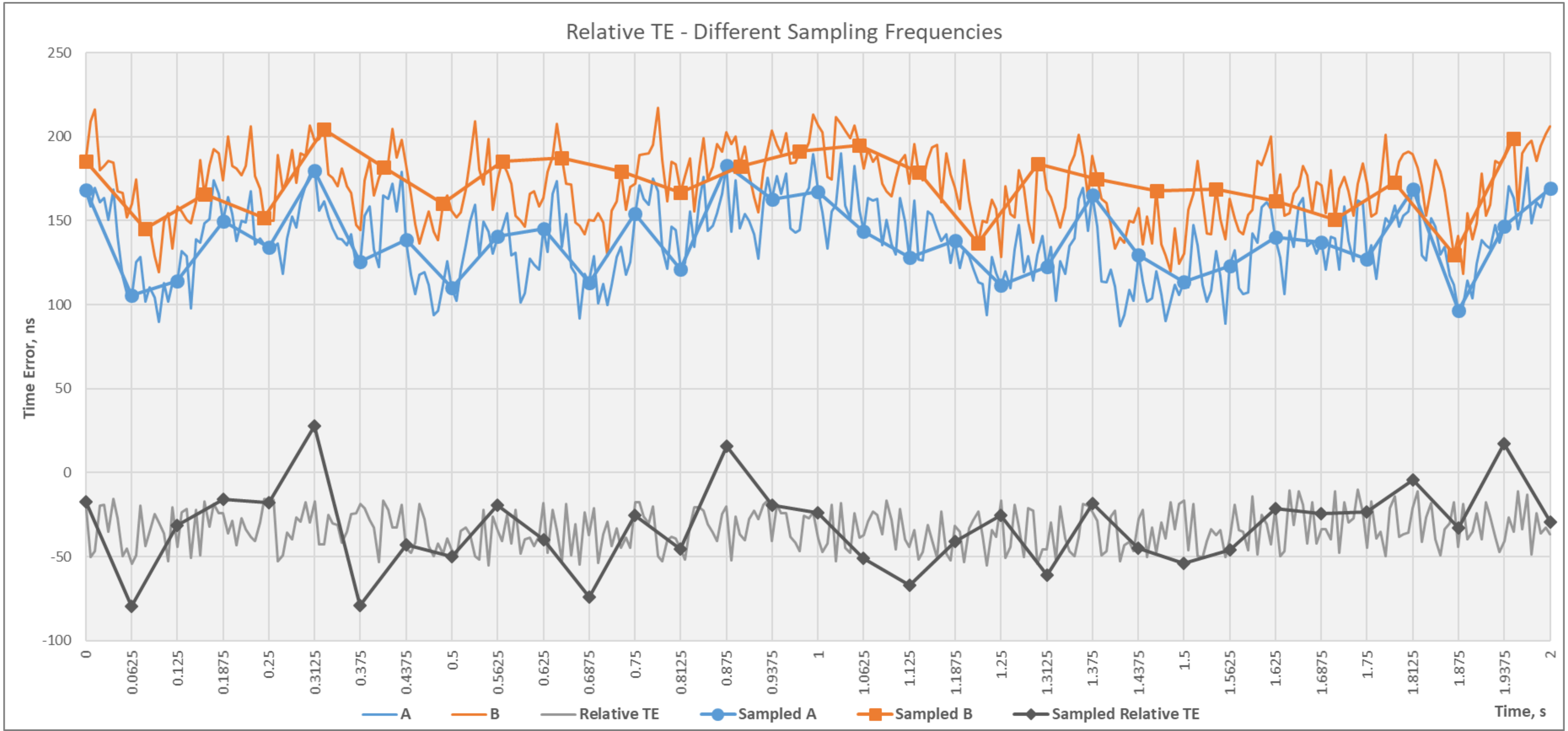
Sampled data



Non-aligned sampling points



Different Sampling Frequency



Measurement Issues for $TE_R(t)$

- Simultaneous measurement required
- Sampling frequency must be aligned
- Sampling points must be aligned
- Not always easy to achieve
  - PTP allows wide variation of sampling rates (±30%)
  - In the field, measurement locations may not be close together, so may not permit simultaneous measurement with the same instrument

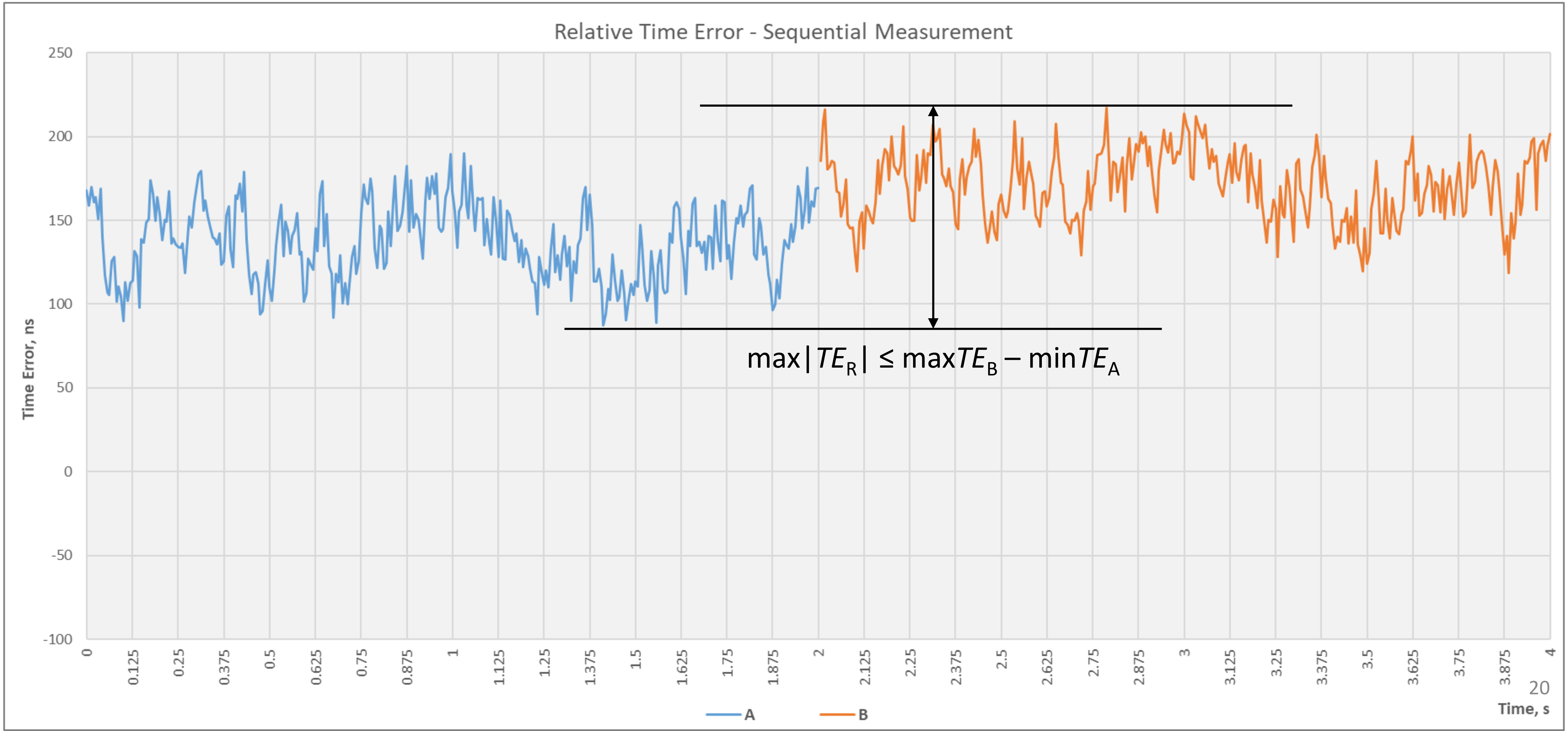
Relationship of max|TE_R| to TAE

- Do we need continuous measurement of $TE_R(t)$?
  - The goal is to control TAE (Time Alignment Error) on the radio signals
  - TAE is defined by 3GPP as "*The largest timing difference between any two signals belonging to different antenna connectors*"
  - Equivalent to the maximum absolute value of $TE_R(t)$, or max|TE_R|
- We can estimate this using the relationship:

$$\max|TE_{\mathrm{R}}|_{\mathrm{A,B}} \leq \textit{the greatest of} \begin{cases} \max TE_{\mathrm{A}} - \min TE_{\mathrm{B}} \\ \max TE_{\mathrm{B}} - \min TE_{\mathrm{A}} \end{cases}$$

- No need for
  - Simultaneous measurement
  - Sampling frequency alignment
  - Sampling point alignment

Estimate of max|TE_R|

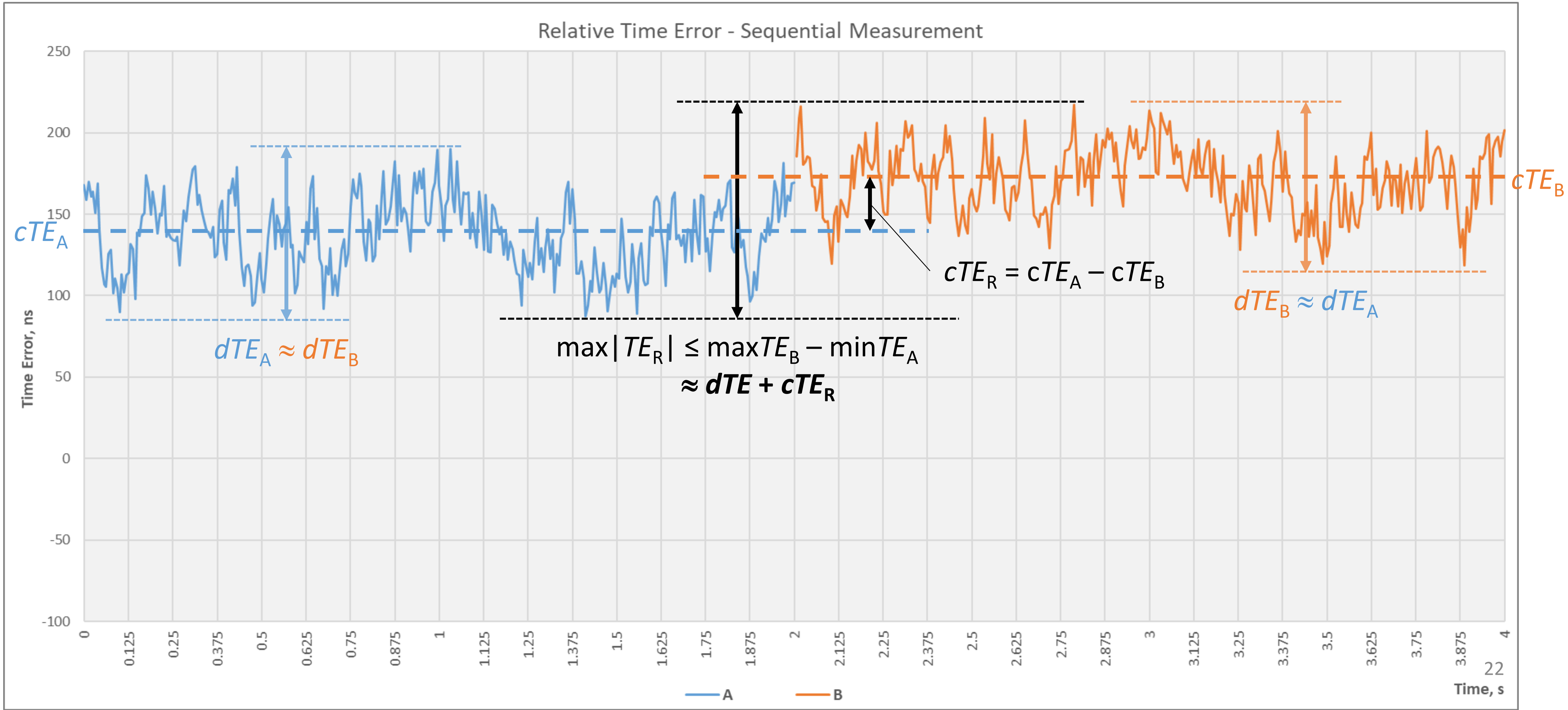


Accuracy of Estimate

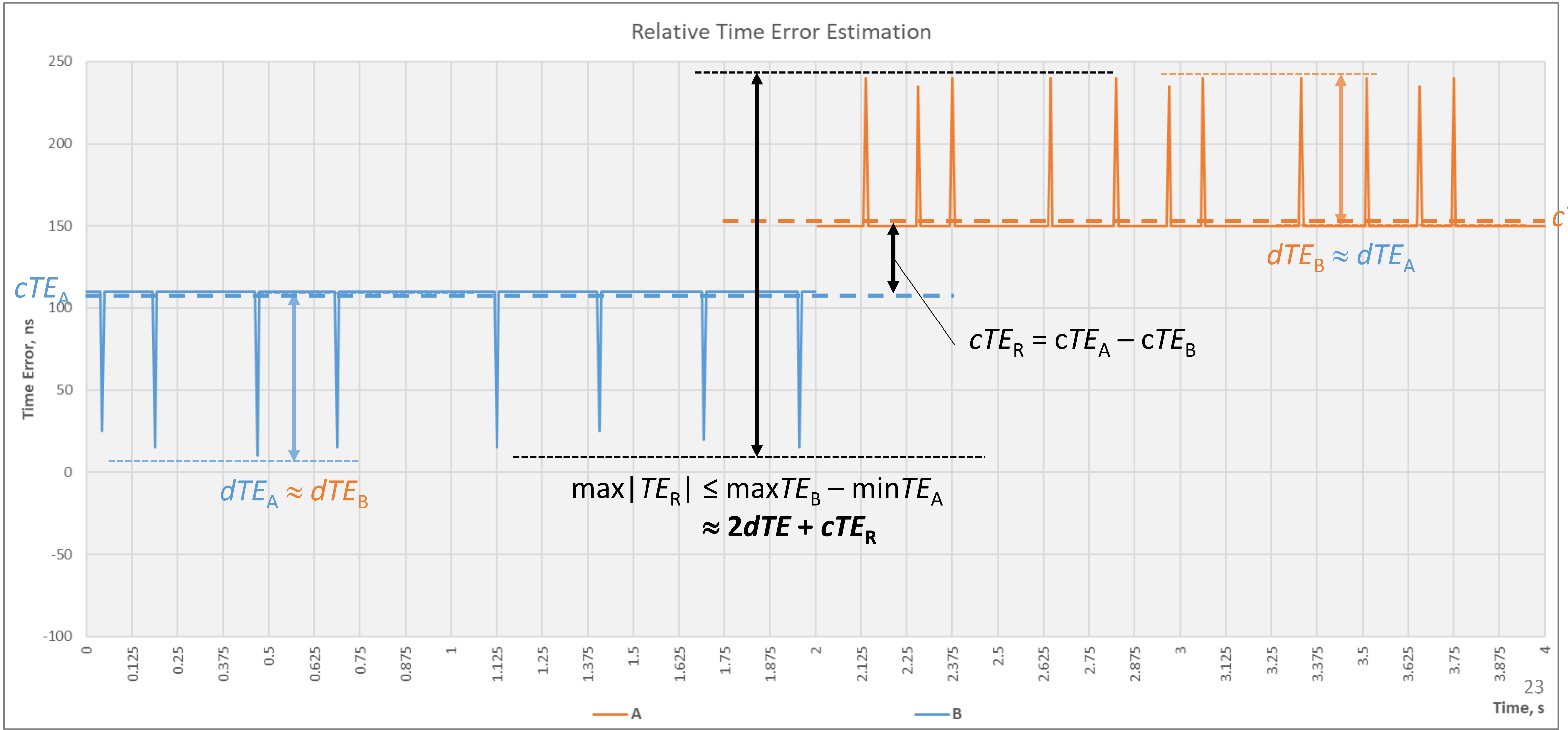
- Always over-estimates
  - Good, as TAE is the limit on the **maximum** time difference
- Doesn't consider common-mode noise
  - Actual TE_R will be lower than estimate if there is correlation in the noise at the measurement points
- Likely to be better than assuming maximum possible spread:
  - If peak-to-peak noise (*dTE*) is *x* ns, and the mean value (*cTE*) is ±*y* ns, then:
  - Maximum possible value of $\max|TE_R|$ is $(2x + 2y)$
  - Estimate will be between $[1x + (y_A - y_B)]$ and $[2x + (y_A - y_B)]$

The difference between the mean values of the two signals, or cTE_R

Estimate of max|TE_R|



Estimate of max|TE_R|



Conclusions

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- Relative time error compliance is going to become much more important with 5G
- Measurement is more complex than before
- It can be simplified by comparing the maximum and minimum time errors of the two *(or more)* relevant signals

- And finally, I nominate Galileo Galilei for a posthumous Time Lord award

Insight and Innovation

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