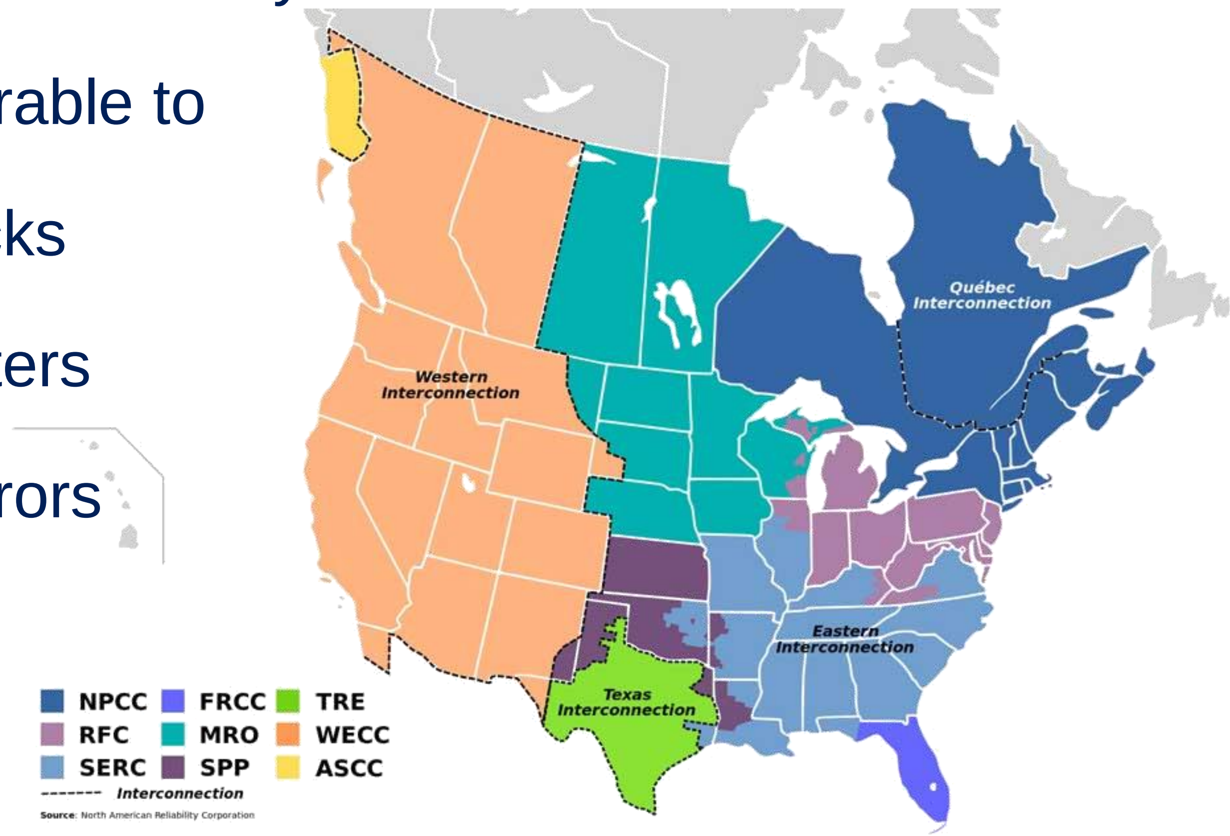
# Multi-Receiver GPS-based Direct Time Estimation for PMUs

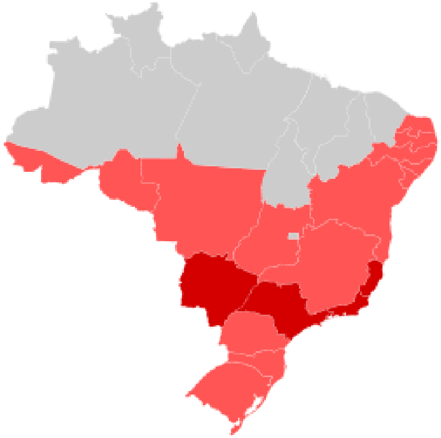
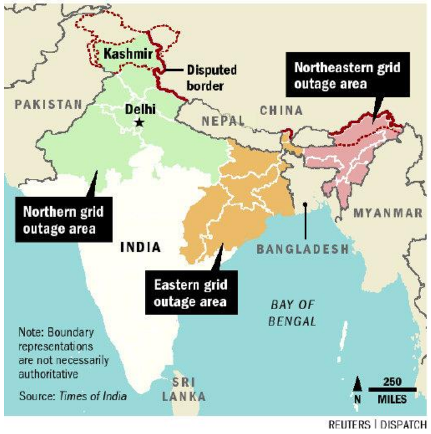
Sriramya Bhamidipati, Yuting Ng and Grace Xingxin Gao

# Motivation

- Supply and demand of electricity should be balanced to maintain power grid stability
- Power grid vulnerable to
  - External attacks
  - Natural disasters
  - Man-made errors



# Massive power blackouts

| Northeast USA 2003 | Java-Bali 2005 | Brazil 2009 | India 2012 |
|---|---|---|---|
|  |  |  |  |
| 50 million people affected | 100 million people affected | 87 million people affected | 670 million people affected |

# Goals of US power community

- Synchronized phasor measurements
- Reliable communication network
- Real-time information monitoring
- Automation of the power grid
- Improving the security margins


Development of
**reliable and robust**
Smart Power Grid

# Goals of US power community

- Synchronized phasor measurements
- Reliable communication network
- Real-time information monitoring
- Automation of the power grid
- Improving the security margins

In use currently **Supervisory Control and Data Acquisition (SCADA)**

# Goals of US power community

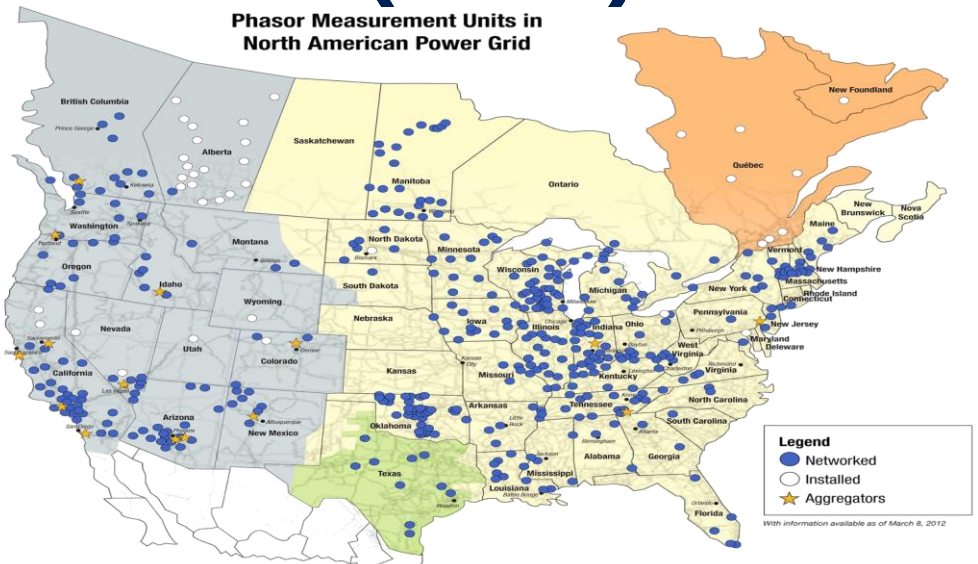
- Synchronized phasor measurements
- Reliable communication network
- Real-time information monitoring
- Automation of the power grid
- Improving the security margins

In use currently **Supervisory Control and Data Acquisition (SCADA)**

Switching to **Phasor Measurement Units (PMUs)**

# Phasor Measurement Unit (PMU)

- Highly synchronized measurements
- PMU measures current and voltage in power grid

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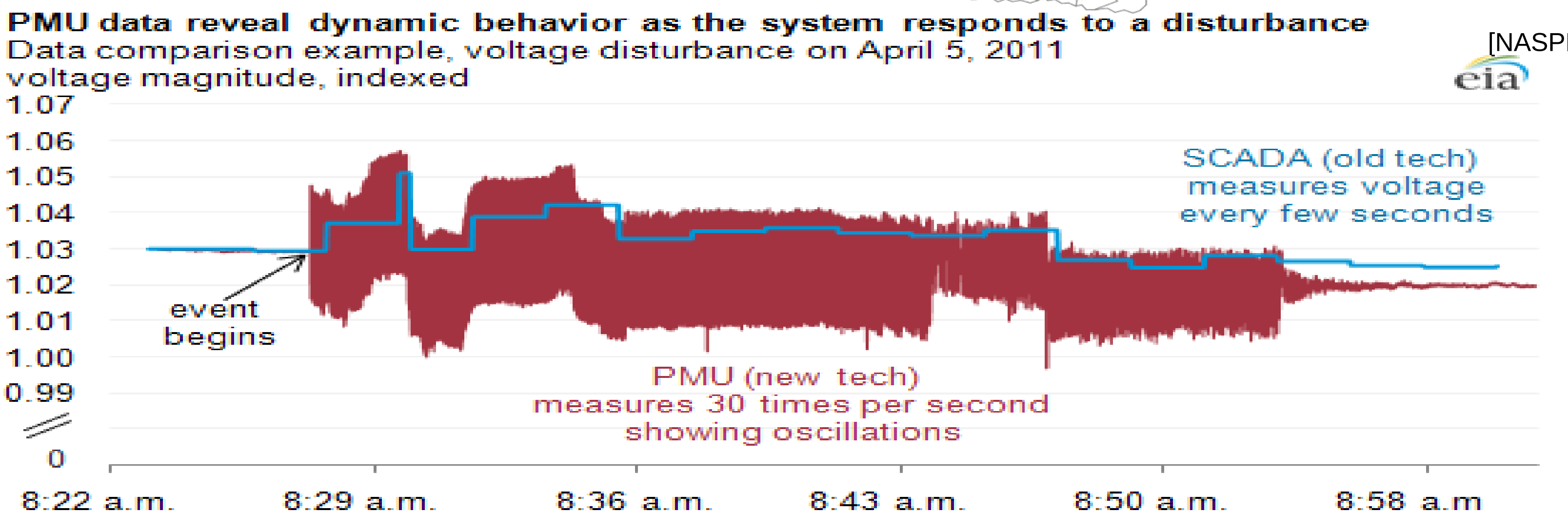
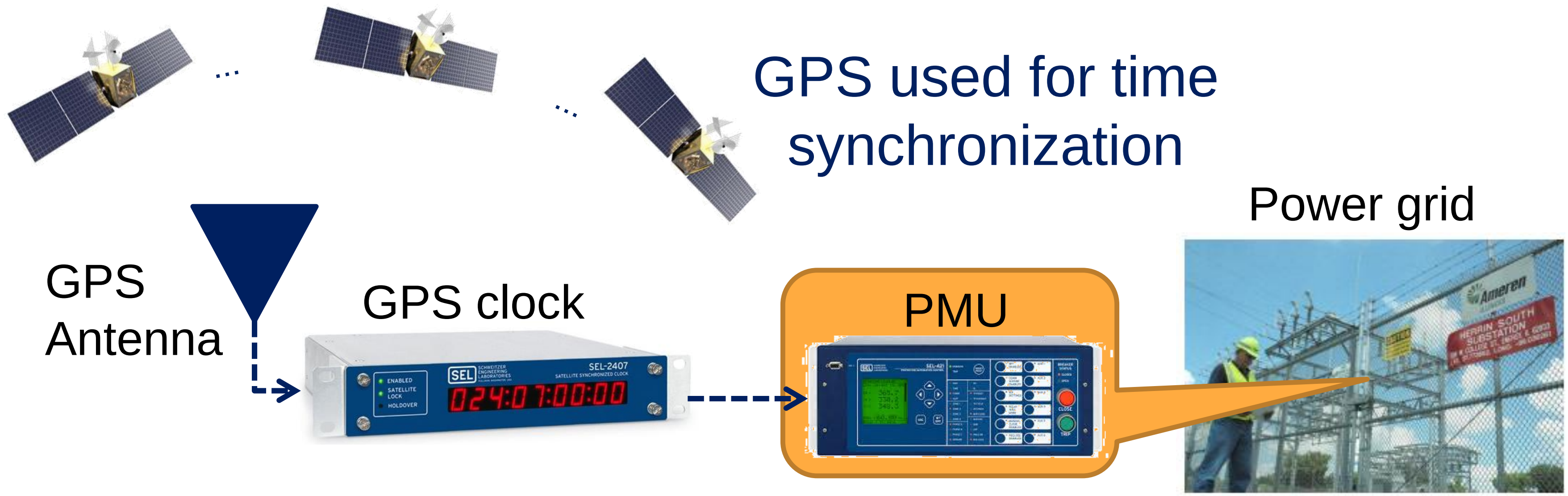


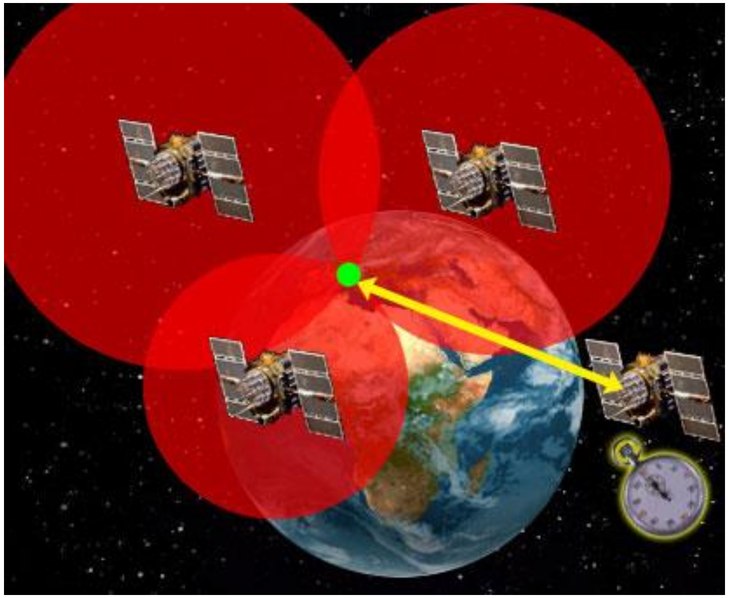
# GPS Timing for PMUs




| Advantages |
|---|
| Global coverage |
| Freely available |
| $\mu s$-level accurate time |

# GPS Conventional Approach

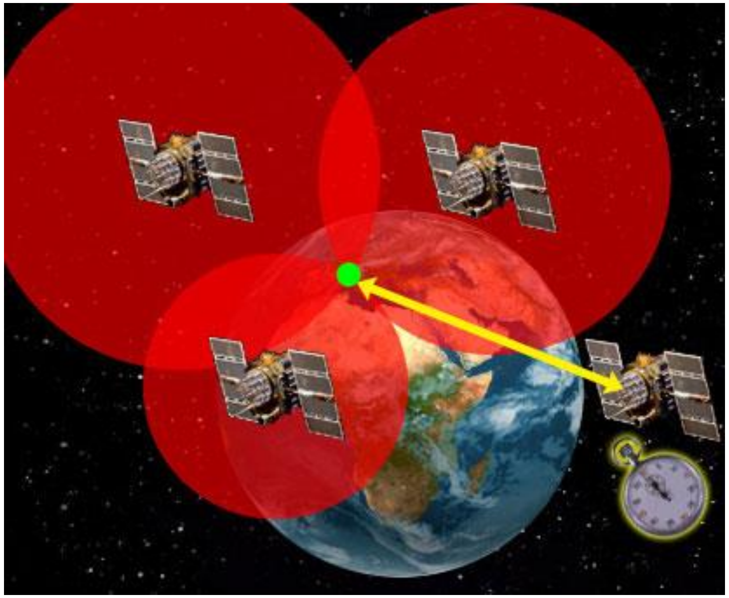
- Inputs
  - Center: 3D satellite position
  - Radius: Pseudoranges
- Unknowns to be estimated:
  - **3D position** $(\mathbf{x}, \mathbf{y}, \boldsymbol{z})$
- Methodology
  - Trilateration technique



Trilateration technique

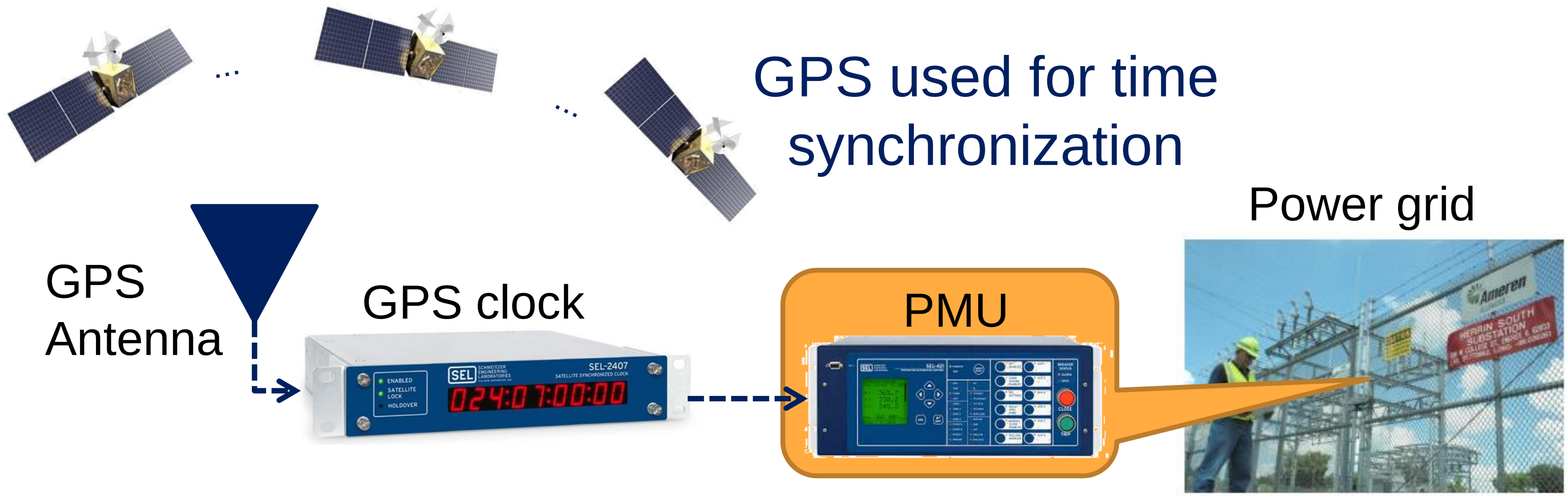
# GPS Conventional Approach

- Inputs
  - Center: 3D satellite position
  - Radius: Pseudoranges
- Unknowns to be estimated:
  - **3D position** $(\mathbf{x}, \mathbf{y}, \boldsymbol{z})$
  - **Clock bias** $(\boldsymbol{c\delta t})$
- Methodology
  - Trilateration technique
  - Minimum 4 satellites required



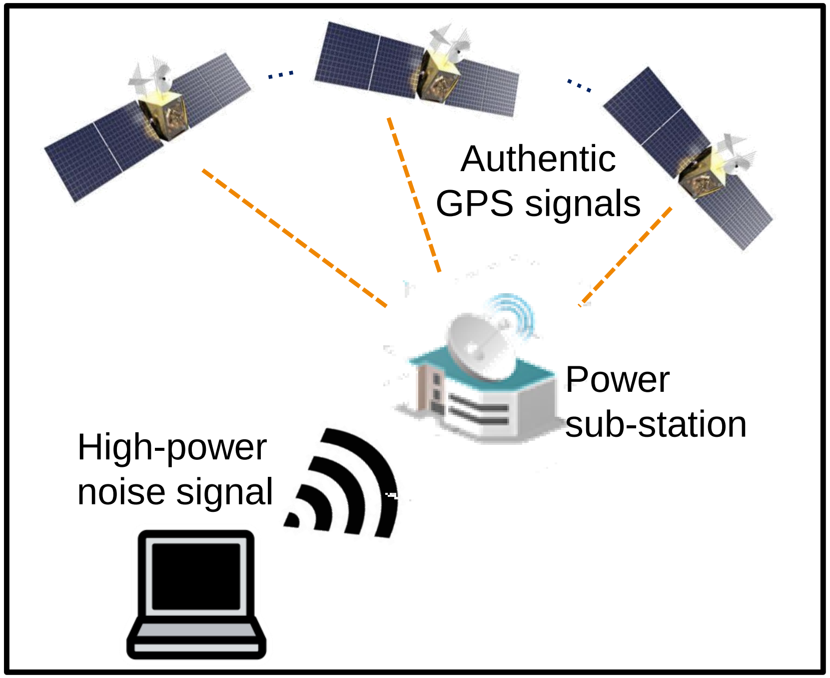
Trilateration technique

# GPS Timing for PMUs

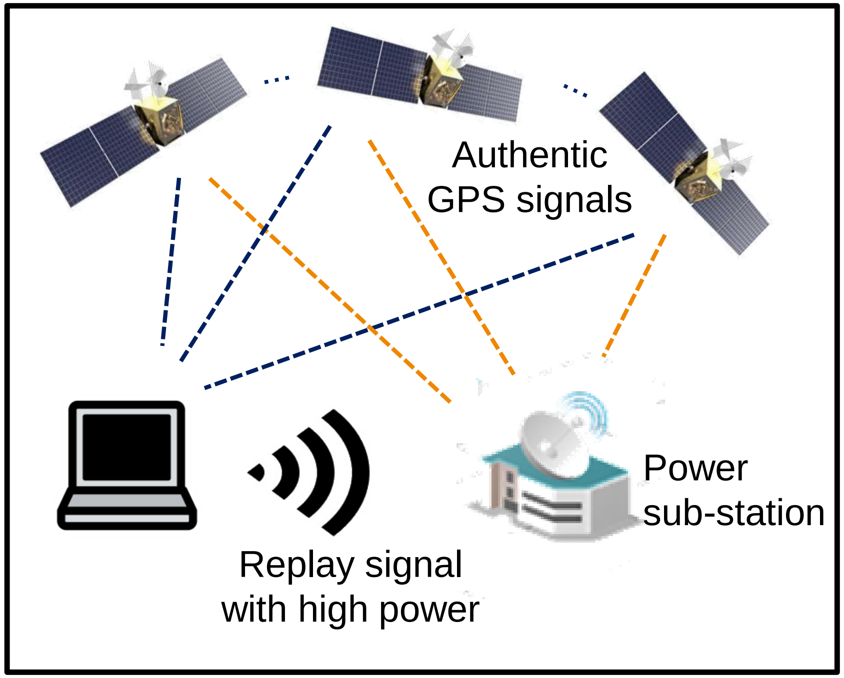



| Advantages | Disadvantages |
|---|---|
| Global coverage | Unencrypted structure |
| Freely available | Low signal power |
| $\mu s$-level accurate time | Vulnerable to attacks |

# GPS Timing Attacks




Jamming: Makes timing unavailable for PMUs

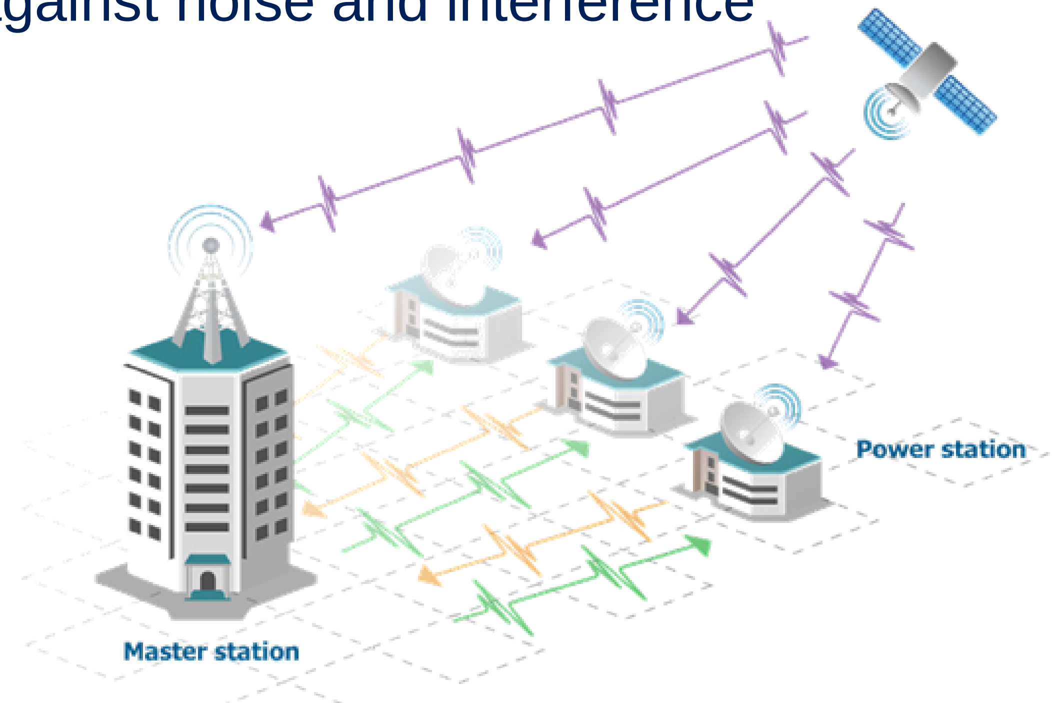



Meaconing: Mislead PMU with wrong time

# Objectives

Propose a robust GPS time transfer technique to:

- Mitigate the effect of external timing attacks
- Improve tolerance against noise and interference



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Multi-Receiver Direct Time Estimation (MRDTE)

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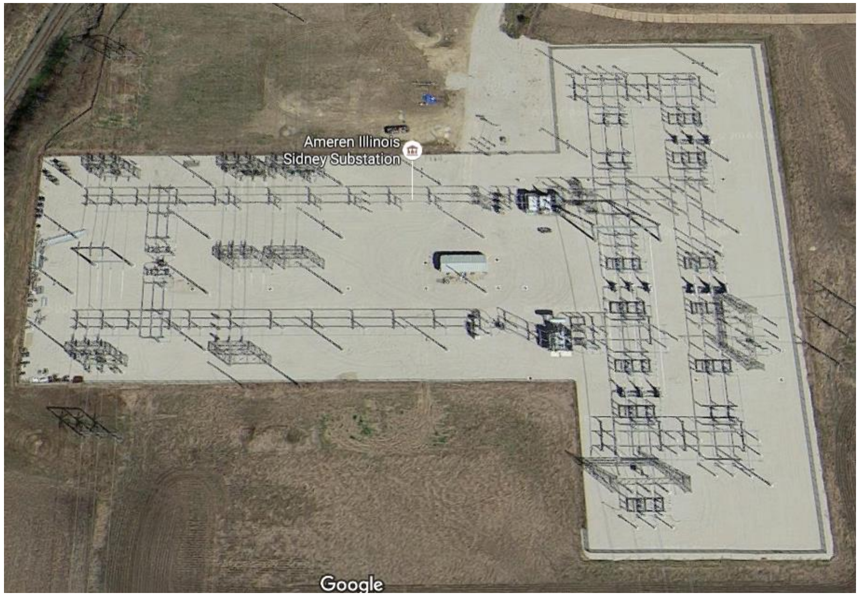
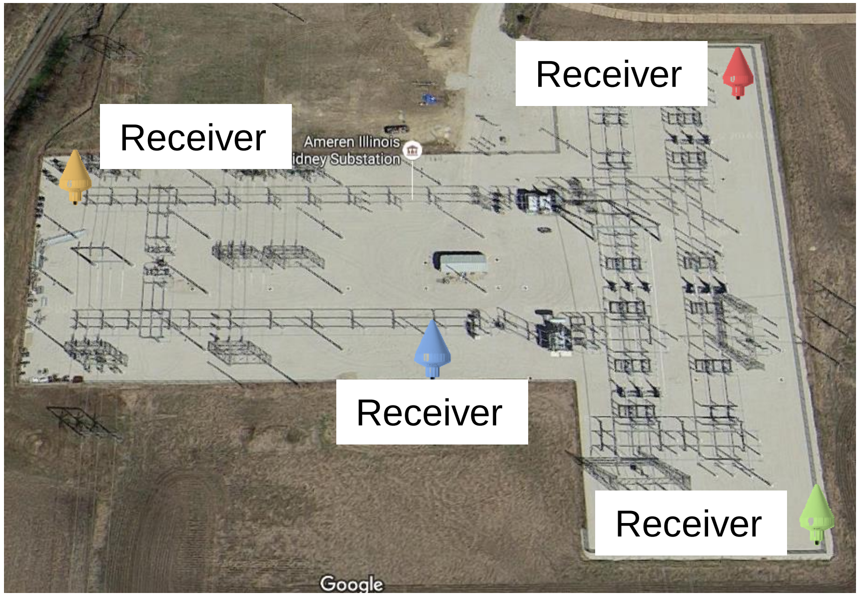
# MRDTE: Approach




Power substation, Sidney, IL

# MRDTE: Approach

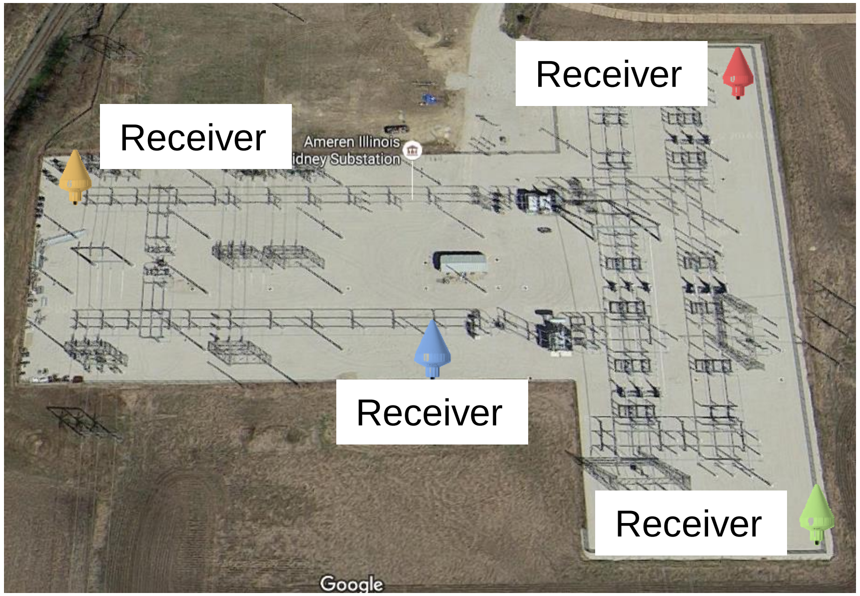
- Multiple receivers
  - Geographical diversity




Power substation, Sidney, IL

# MRDTE: Approach

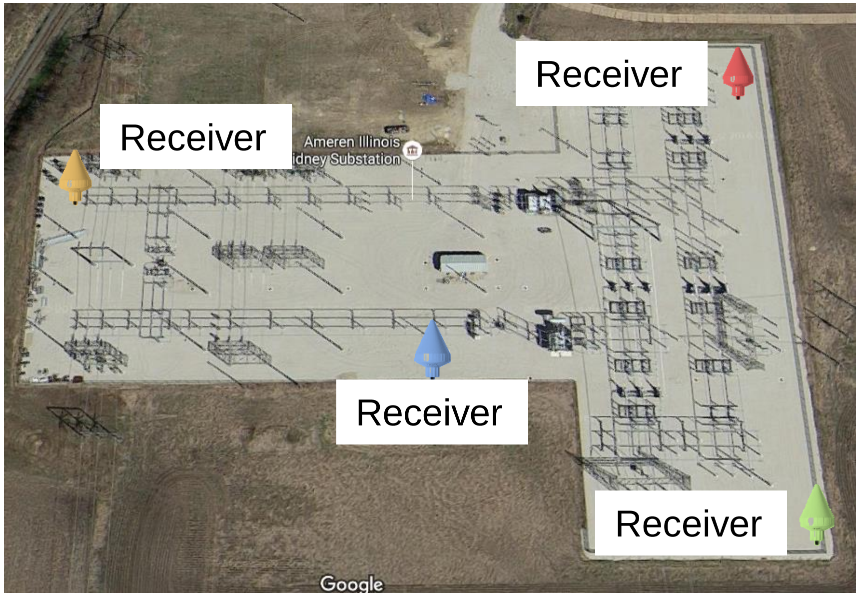
- Multiple receivers
  - Geographical diversity
- Position Aiding
  - Static receiver location




Power substation, Sidney, IL

# MRDTE: Approach

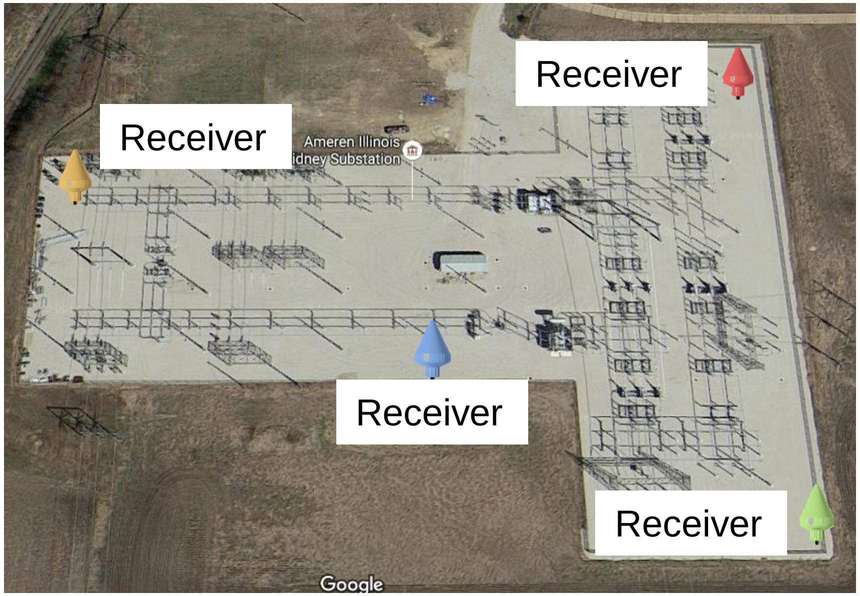
- Multiple receivers
  - Geographical diversity
- Position Aiding
  - Static receiver location
- Direct Time Estimation (DTE)
  - Works with timing parameters
  - No intermediate pseudoranges




Power substation, Sidney, IL

# MRDTE: Approach

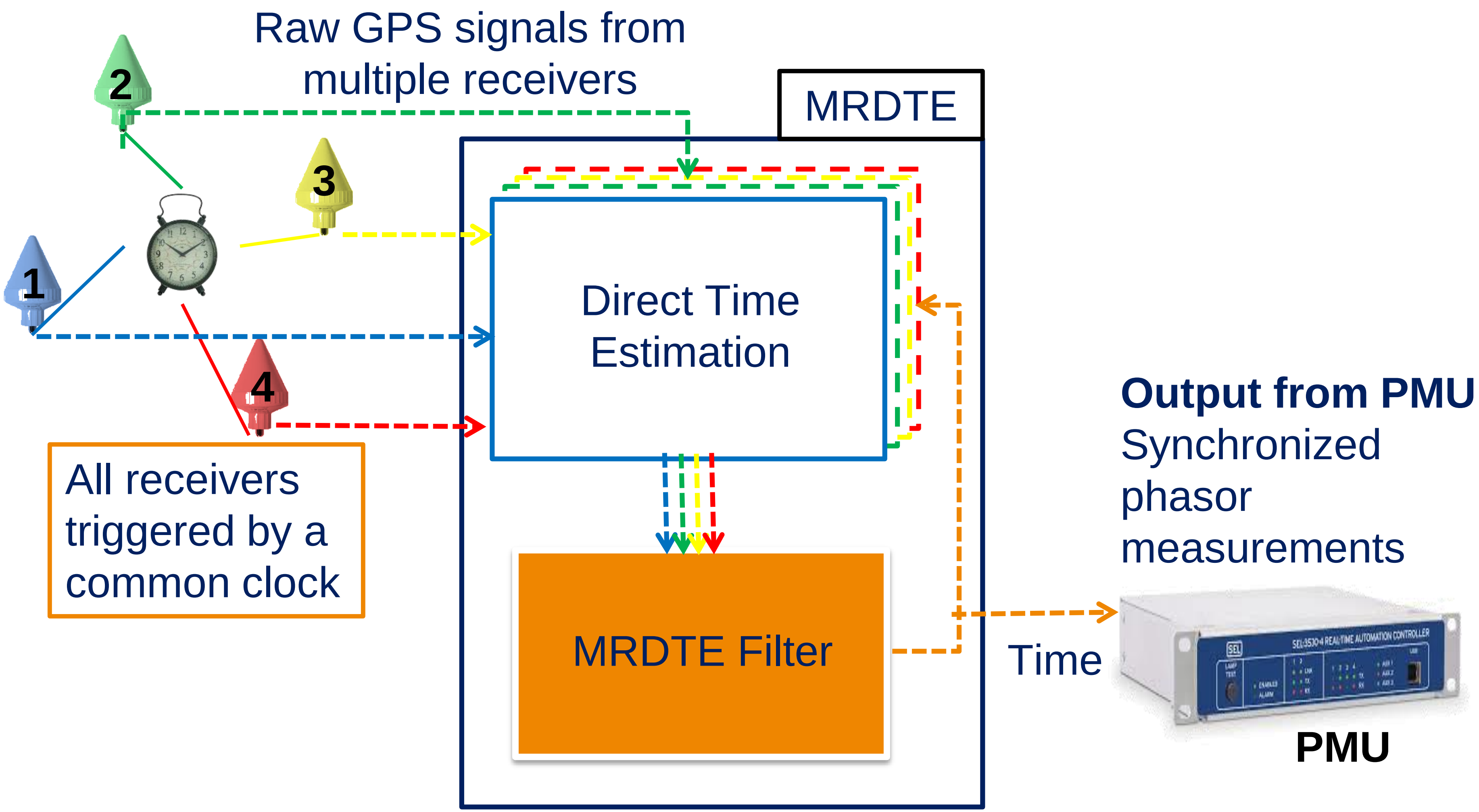
- Multiple receivers
  - Geographical diversity
- Position Aiding
  - Static receiver location
- Direct Time Estimation (DTE)
  - Works with timing parameters
  - No intermediate pseudoranges
- Triggered by common external clock



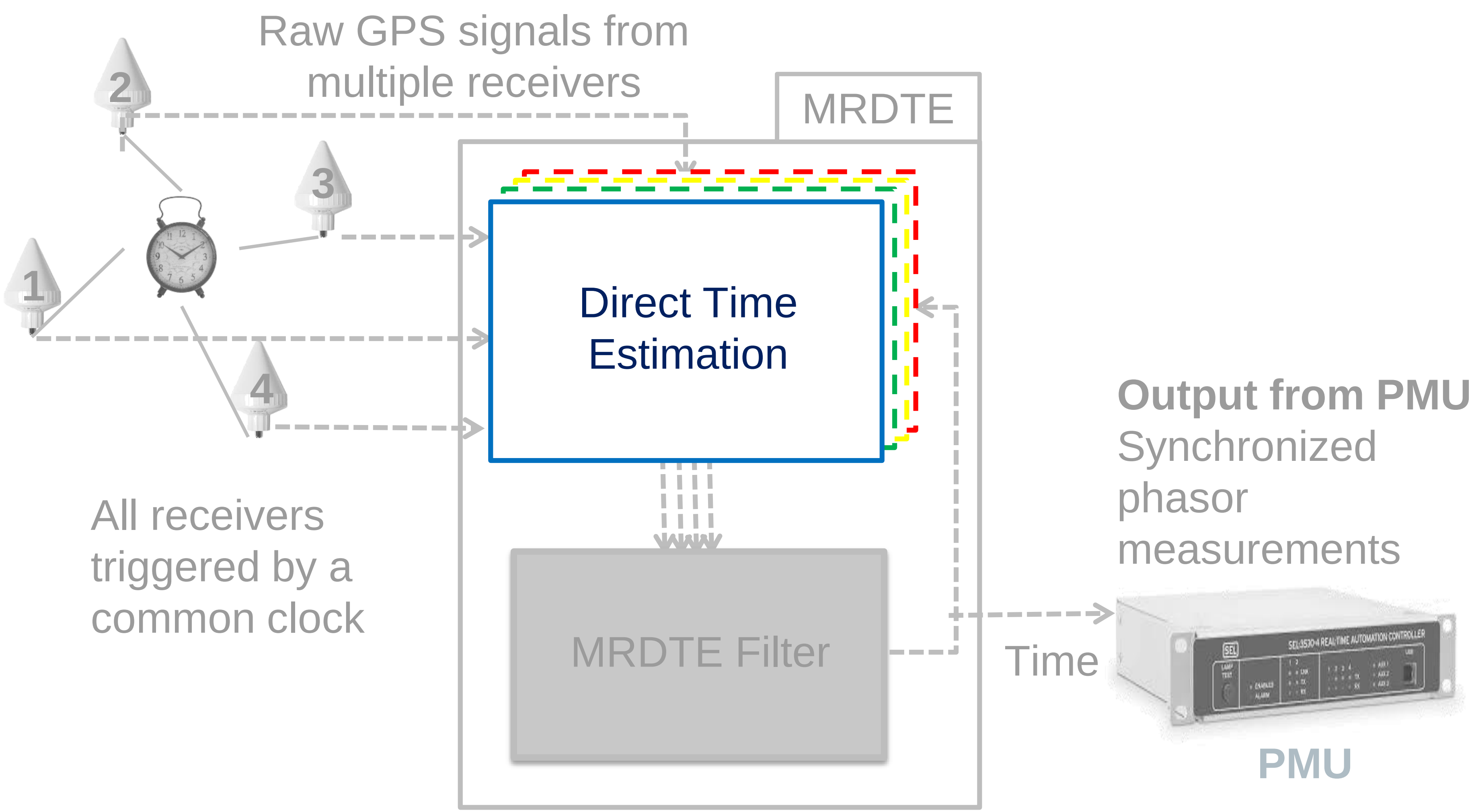

Power substation, Sidney, IL

Reduction in no. of unknowns from
8 $(x, y, z, c\delta t, \dot{x}, \dot{y}, \dot{z}, c\dot{\delta t})$ × # of receivers to 2 $(c\delta t, c\dot{\delta t})$

# MRDTE: Architecture

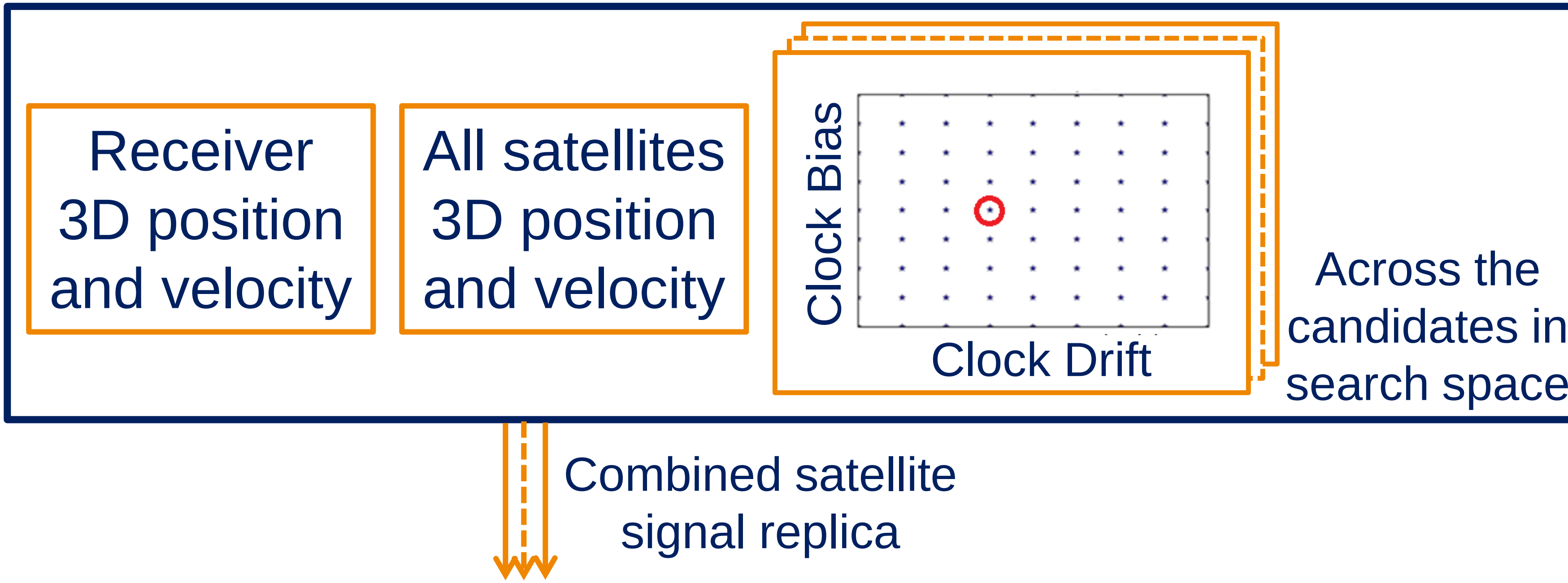


# MRDTE: Architecture

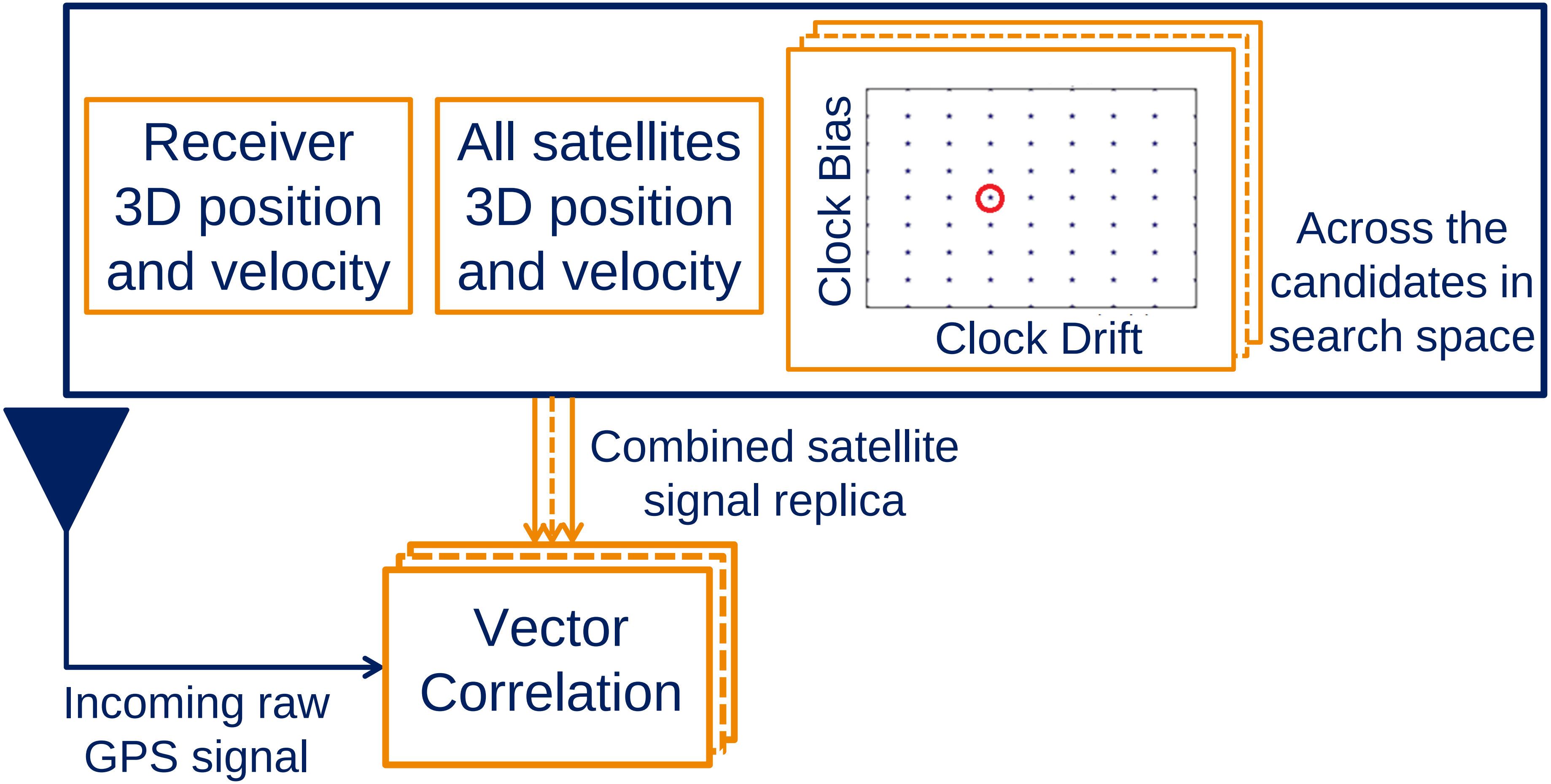



**Output from PMU:** Synchronized phasor measurements

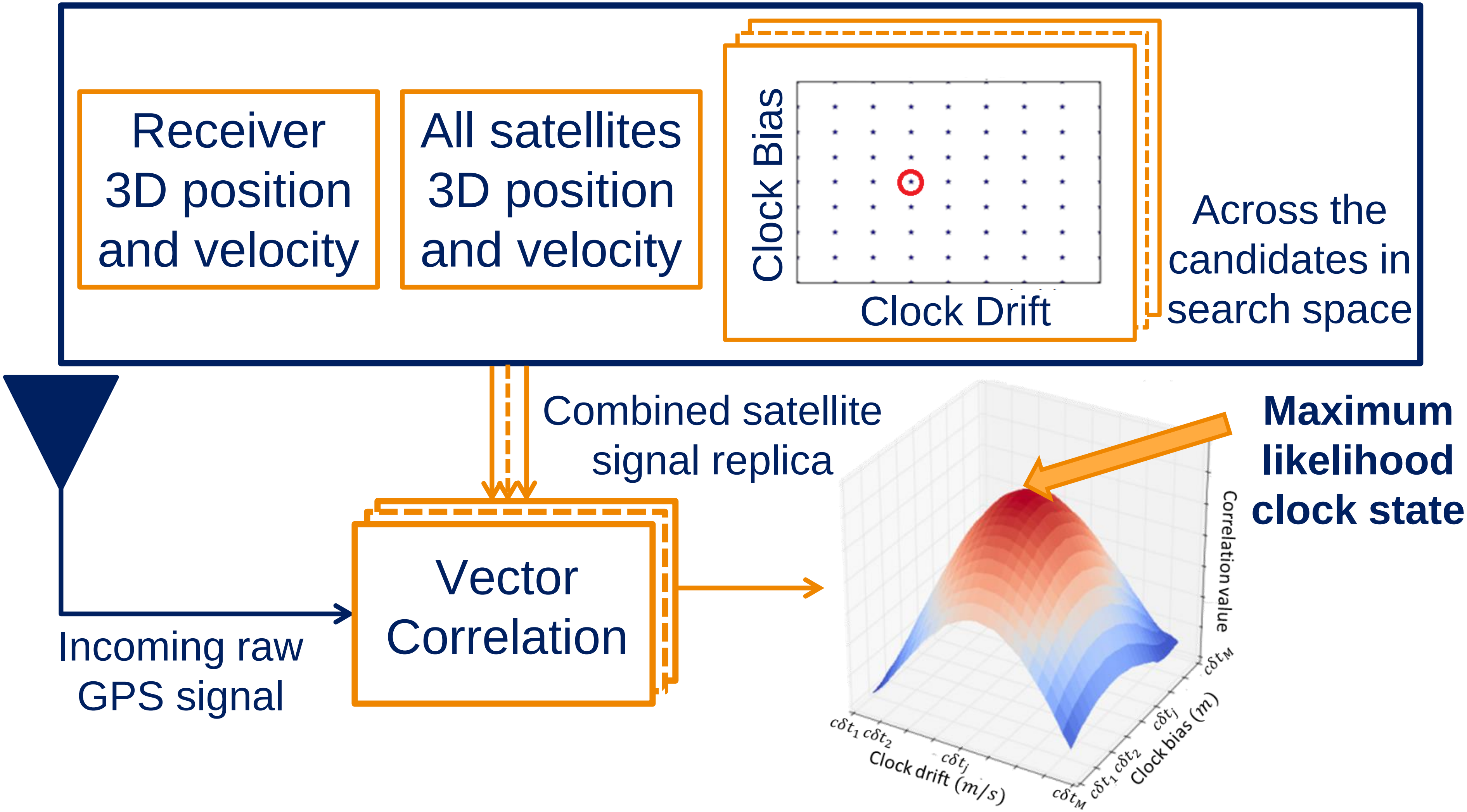
# Direct Time Estimation



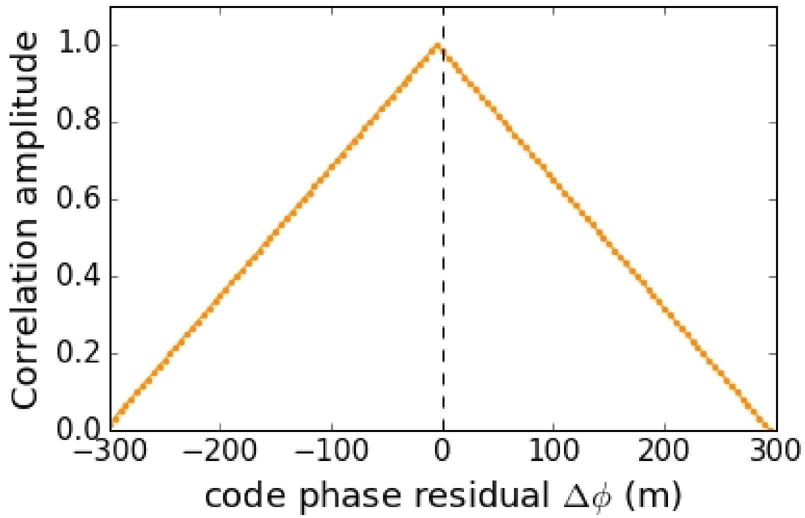
# Direct Time Estimation

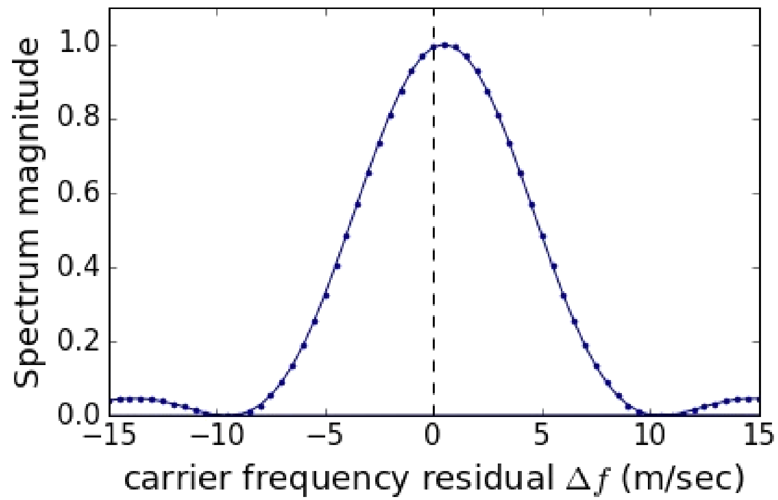


# Direct Time Estimation



# DTE: Vector Correlation



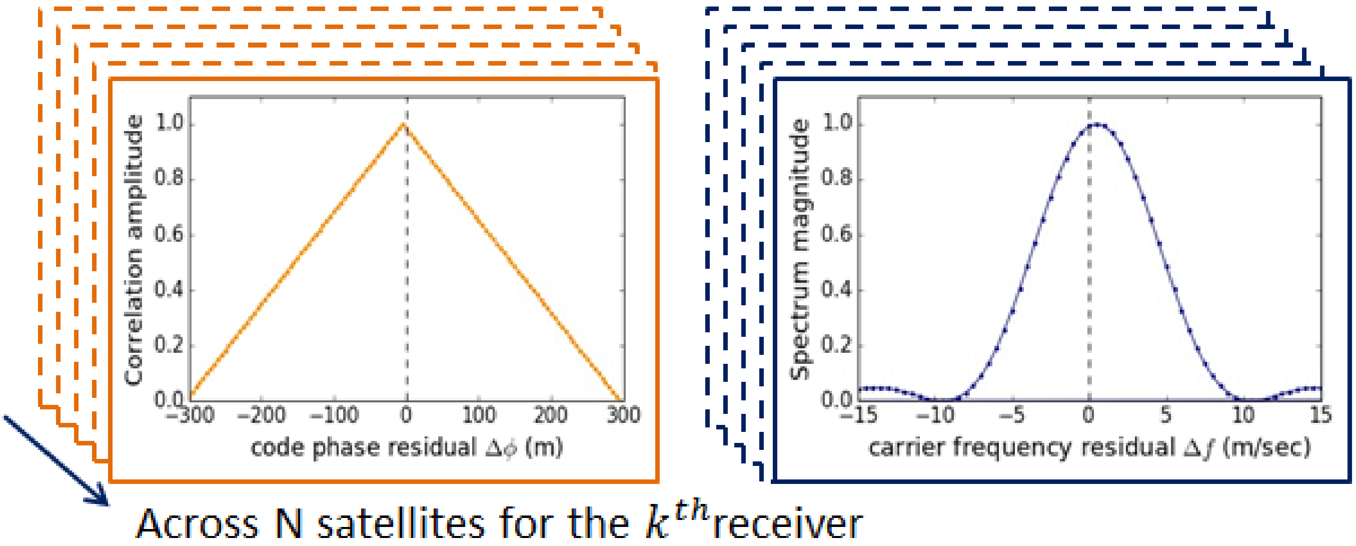

Code phase depends on clock bias

Carrier frequency depends on clock drift

Code residual ($\Delta\phi_{code}$) , Carrier residual ($\Delta f_{carr}$) independently estimated in two parallel threads

# DTE: Vector Correlation Continued

Direct correlation involves non-coherent summation




- Non-coherent summation across satellites to track code phase and carrier frequency.

# DTE: Max Likelihood Estimation

$$corr_j = corr\left(R, \sum_{i=1}^{N} Y^i(c\delta t_j, c\delta \dot{t}_j)\right)$$

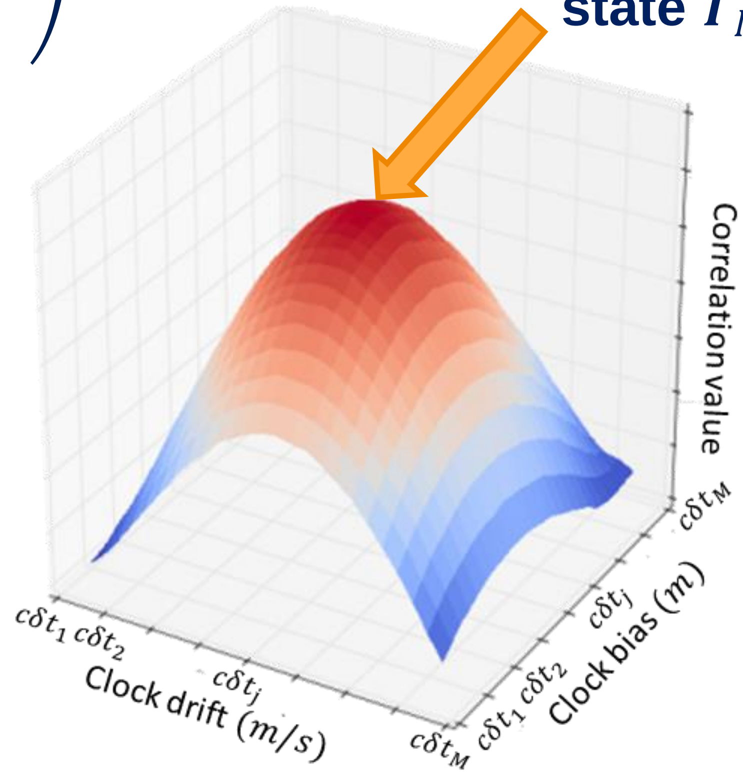
$$T_{MLE} = \max_{j=1,..,P} corr_j$$
$$= [c\delta t_{MLE}, c\delta \dot{t}_{MLE}]$$

Where,

$P$= number of grid points

$R$= incoming raw GPS signal

$Y^i$= $i^{th}$satellite signal replica

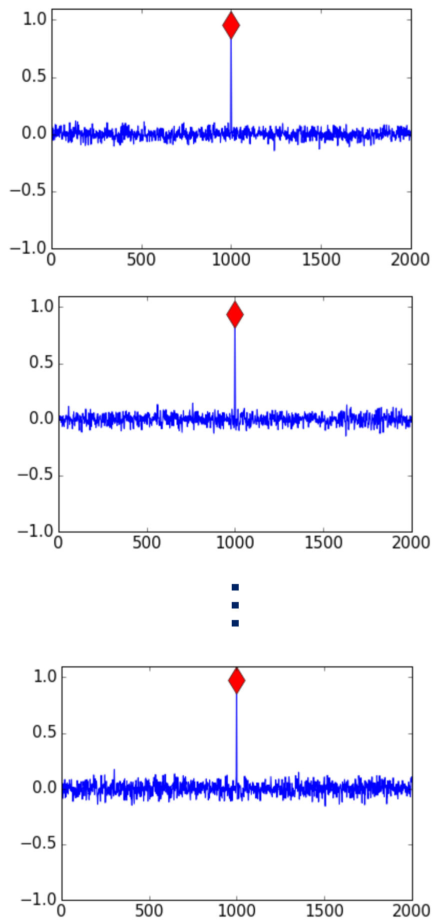


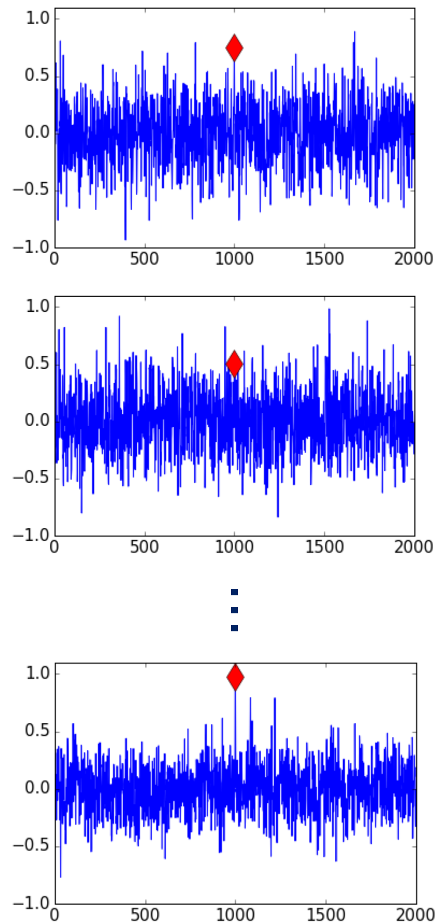
# DTE: Robustness

Strong signal environment

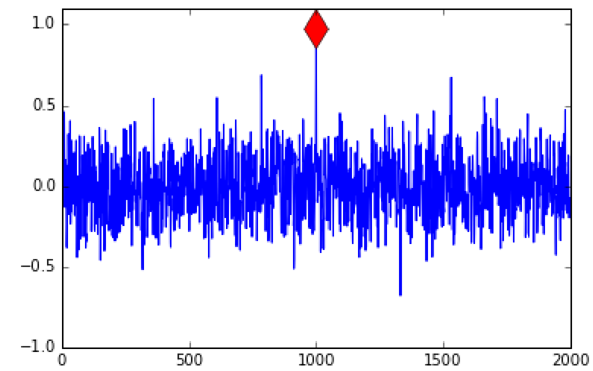
Weak signal environment

Across the satellites



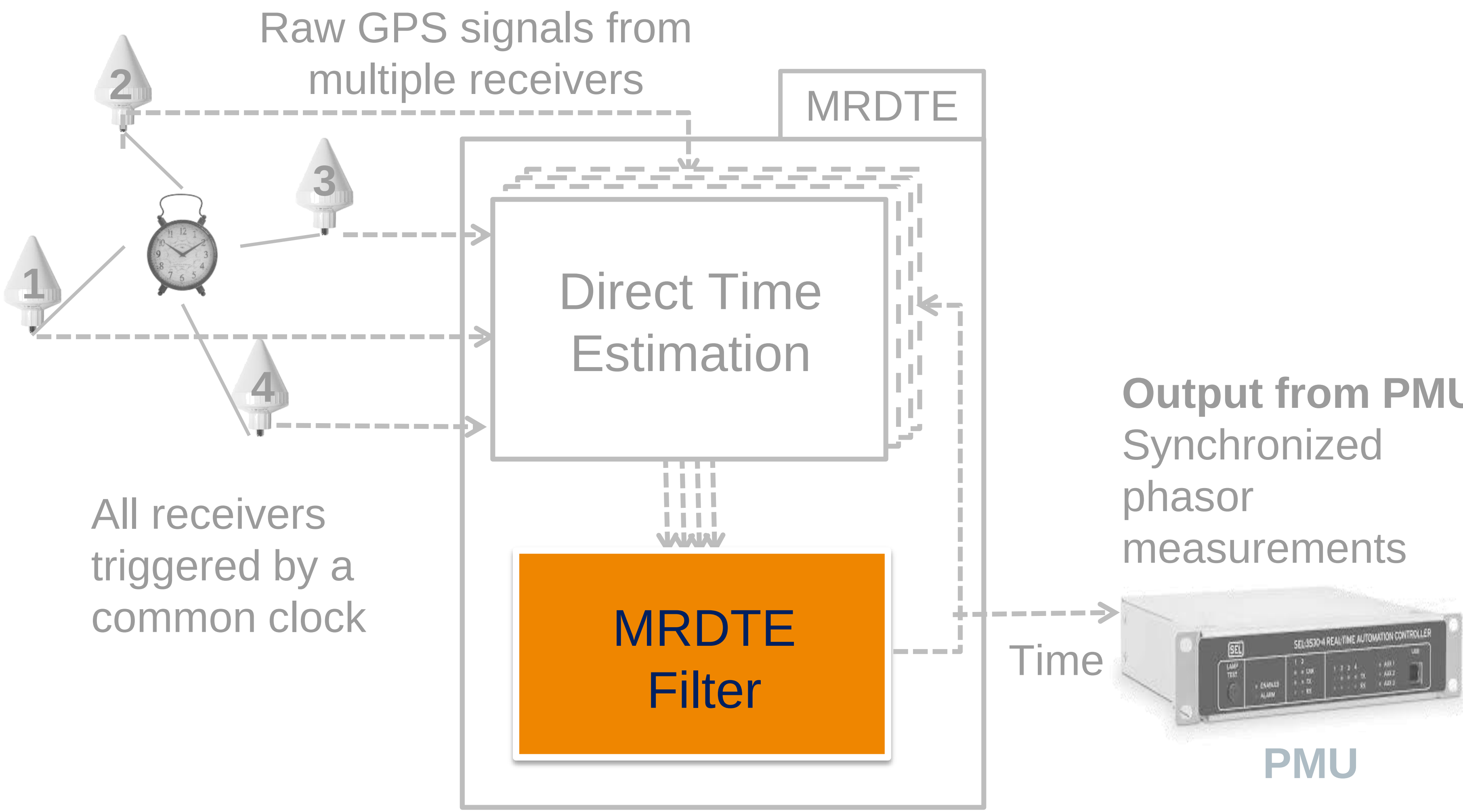




Direct Time Estimation




Direct Time Estimation more robust than Scalar Tracking

# MRDTE: Architecture

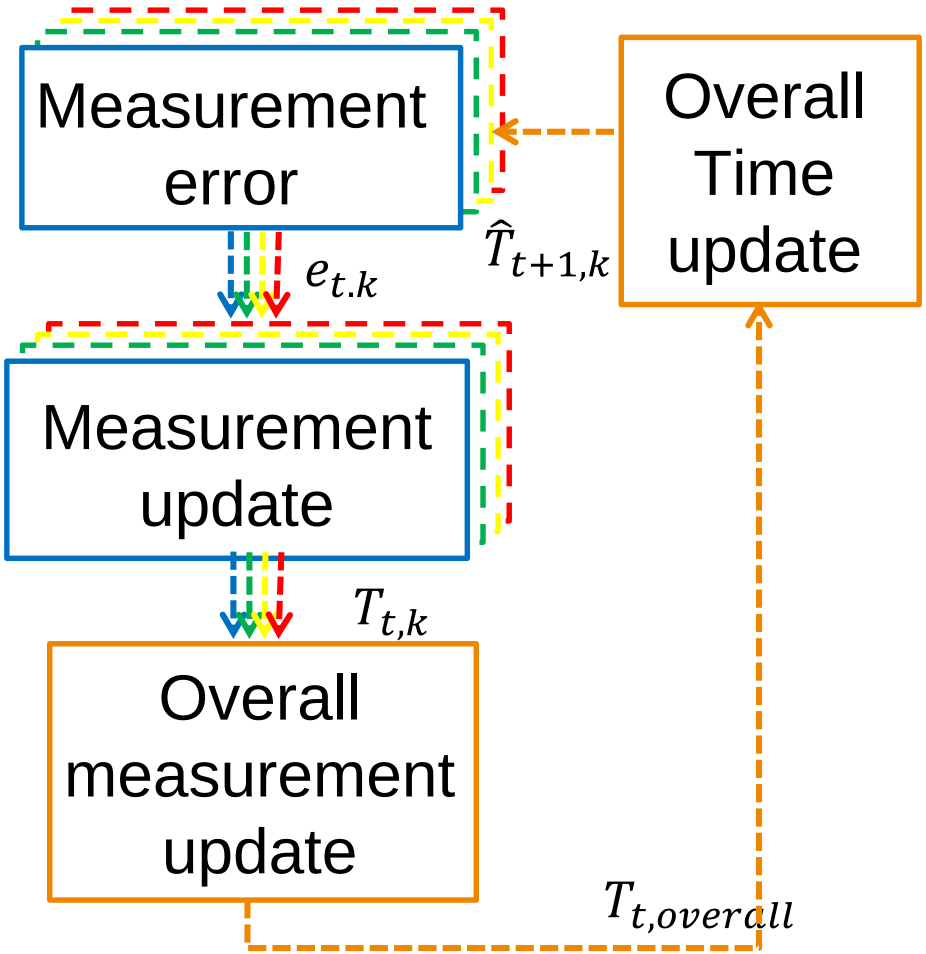


# MRDTE Filter: Kalman Filter

- Prediction model:

$$\hat{T}_{t+1,k} = \begin{bmatrix} 1 & \Delta T \\ 0 & 1 \end{bmatrix} T_{t,overall}$$

- State vector $T_{t,k} = \begin{bmatrix} c\delta t_k \\ c\delta \dot{t}_k \end{bmatrix}$
- Error covariance matrix is calculated by processing the last 19 measurement errors

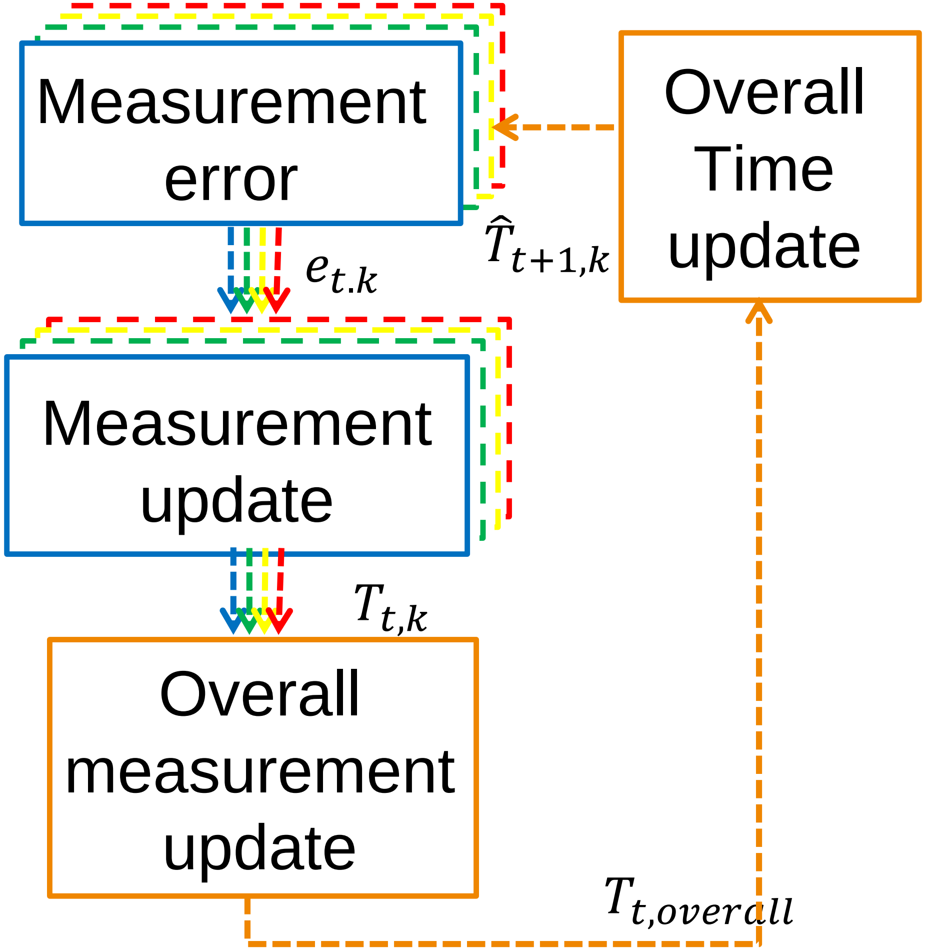


# MRDTE Filter: Overall Filter

- Overall filter to obtain the final corrected clock state $T_{t,overall}$
- Measurement error matrix

$$e_{t,overall} = \begin{bmatrix} T_{t,1} - \hat{T}_{t,overall} \\ \vdots \\ T_{t,k} - \hat{T}_{t,overall} \\ T_{t,L} - \hat{T}_{t,overall} \end{bmatrix}$$

Where $T_{t,k} = \begin{bmatrix} c\delta t_k \\ c\delta \dot{t}_k \end{bmatrix}$ $k = 1..L$



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GPS Conventional approach

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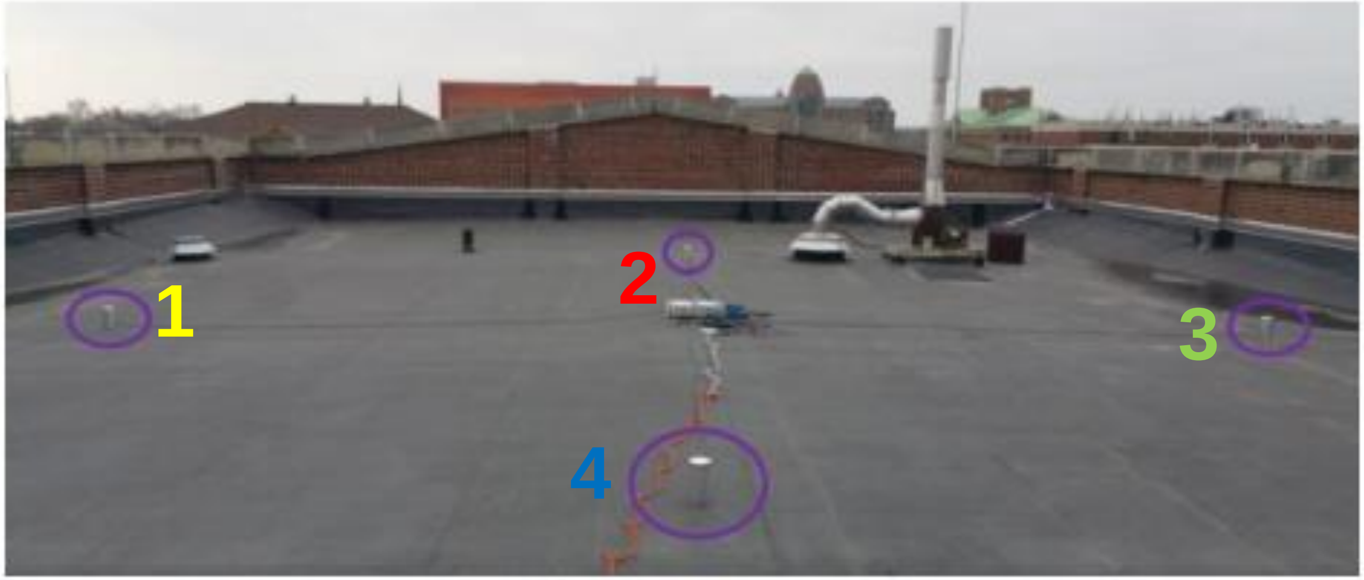
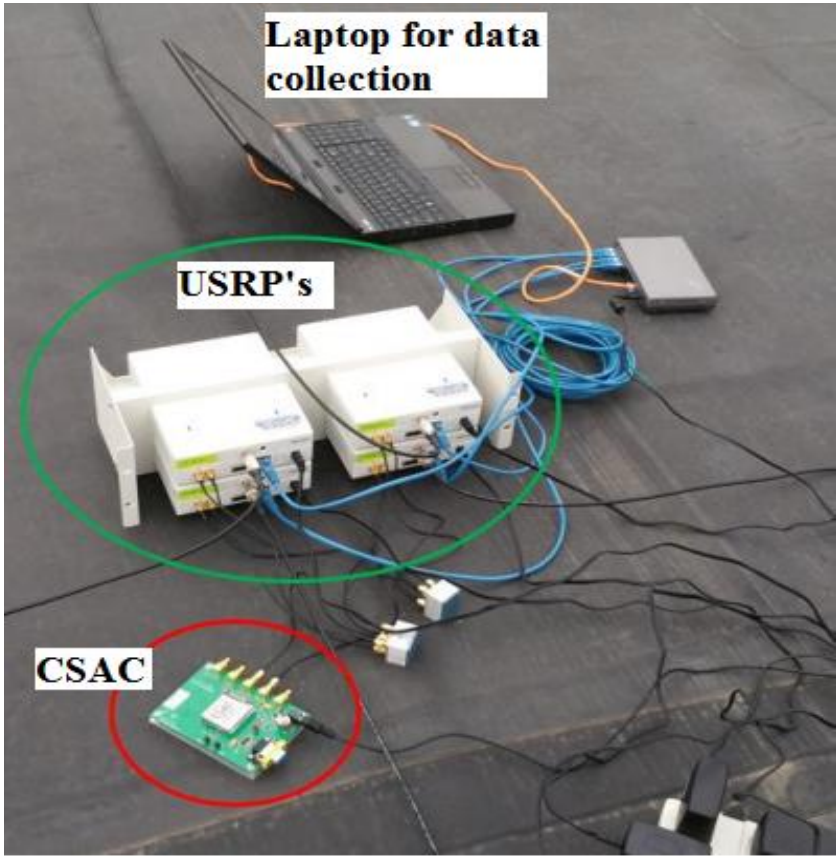
# Experimental Setup




- 4 receivers on the rooftop of Talbot Lab, Urbana, Illinois
- Placed along the corners of square with diagonal length 10m
- Mimic the setup of a original power substation

# Experimental Setup: Continued

- 4 USRP’s used for collecting GPS signals
- All the receivers triggered by a common external clock - Chip Scale Atomic Clock (CSAC)
- For processing the data: pyGNSS - object oriented python platform developed by our lab



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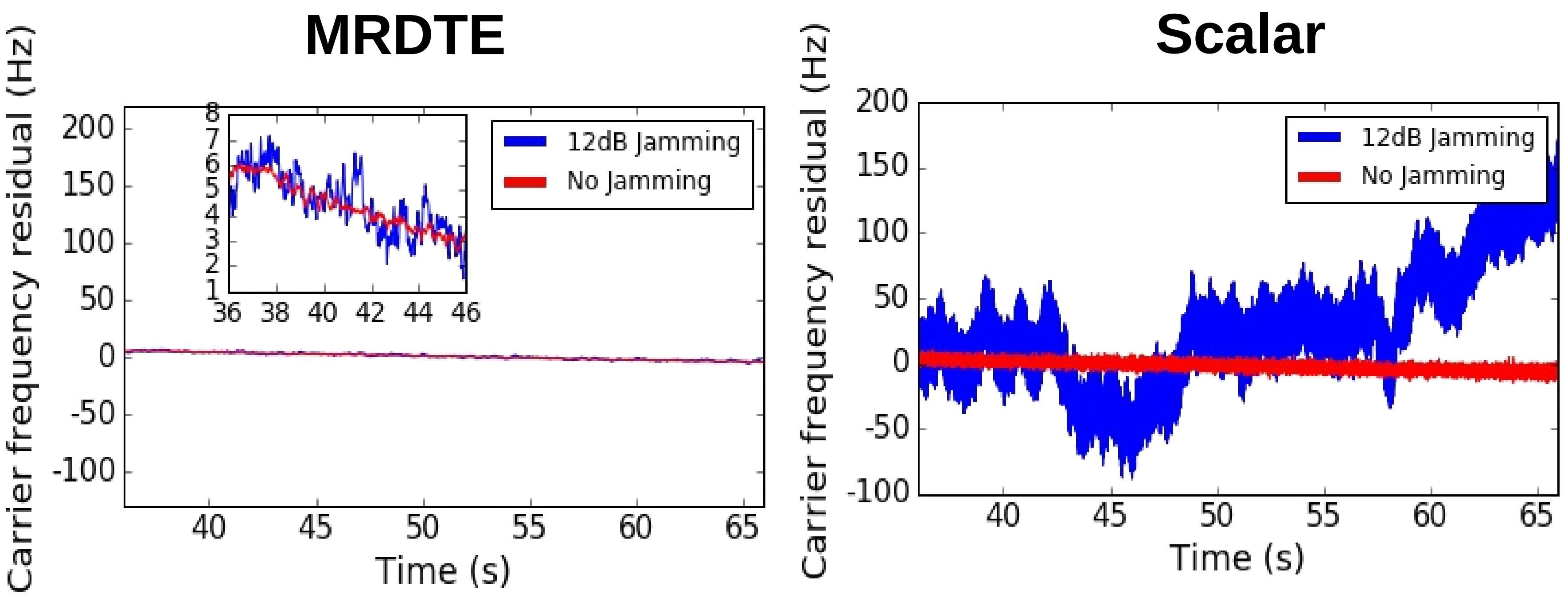
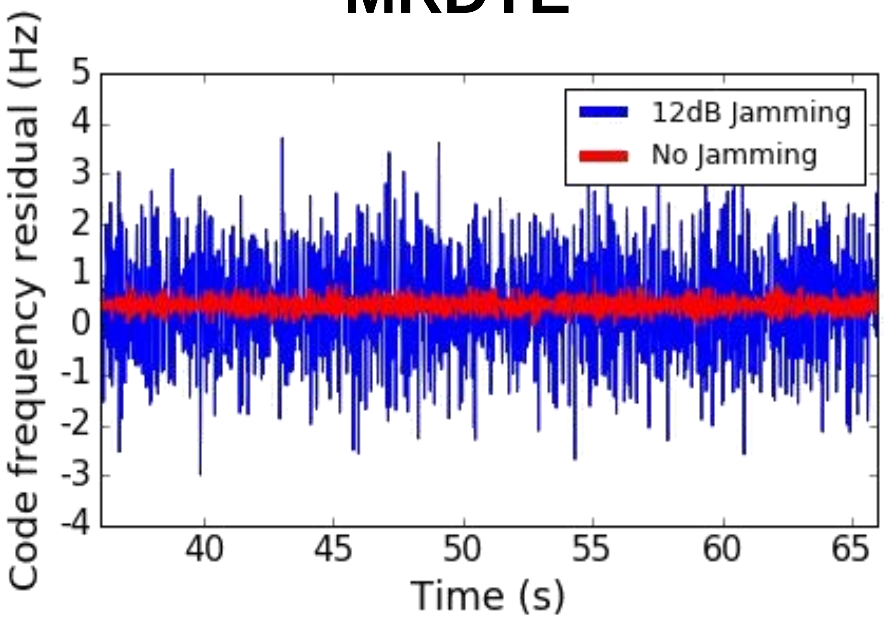
# Jamming: Carrier Frequency



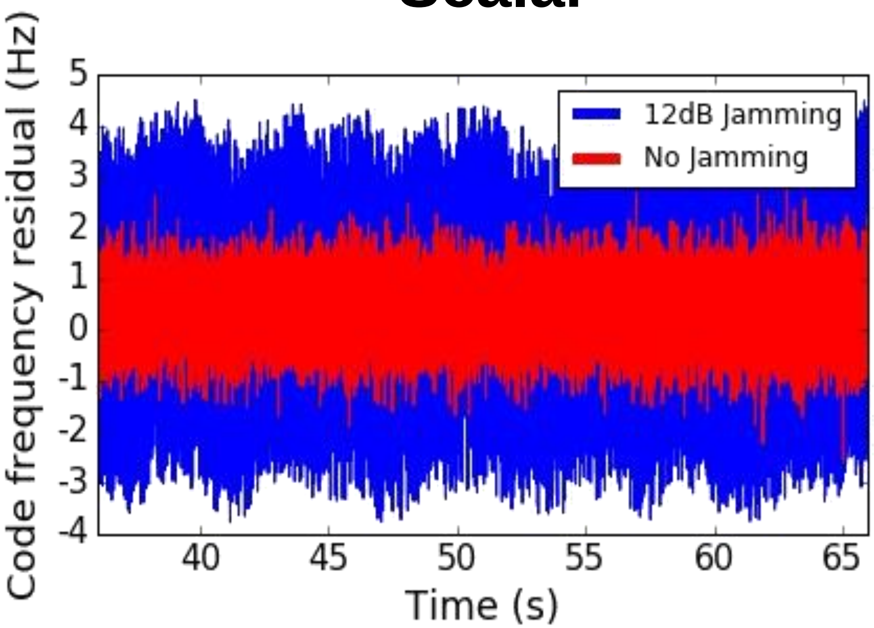

MRDTE (loses track at 17dB added jamming)
offers **5dB** more noise tolerance than
Scalar Tracking (loses track at 12dB added jamming)

# Jamming: Code Frequency

**MRDTE**



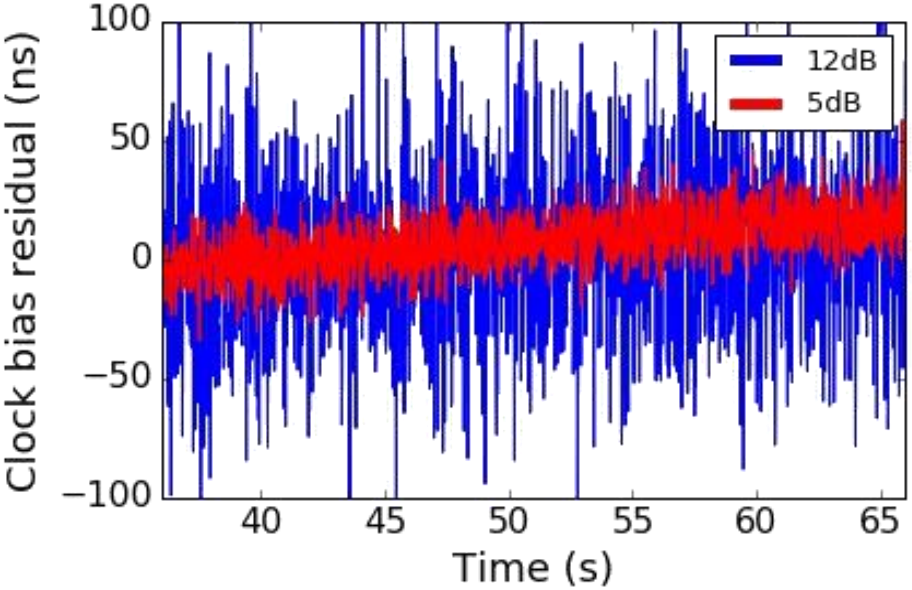

**Scalar**



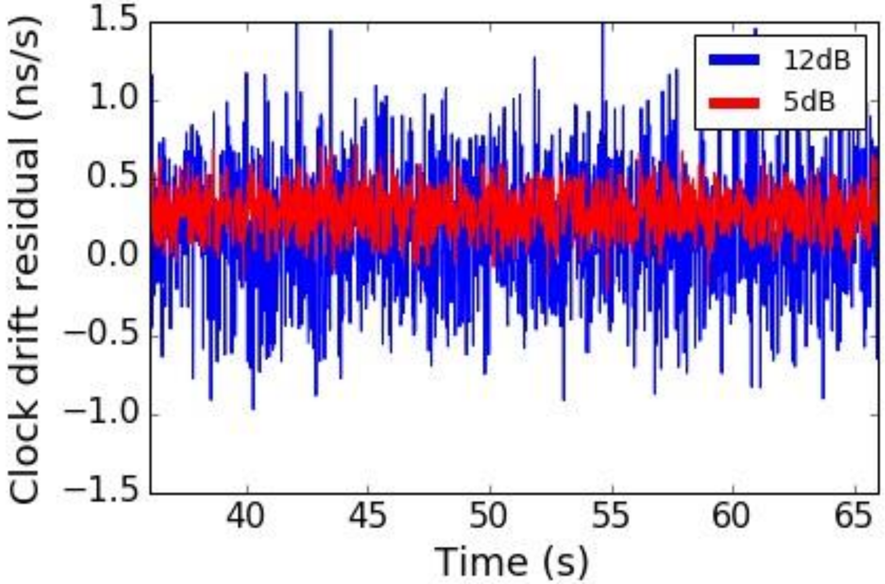

MRDTE offers better convergence and smaller variance to external noise interference

# Jamming: Different Levels

**Clock bias**



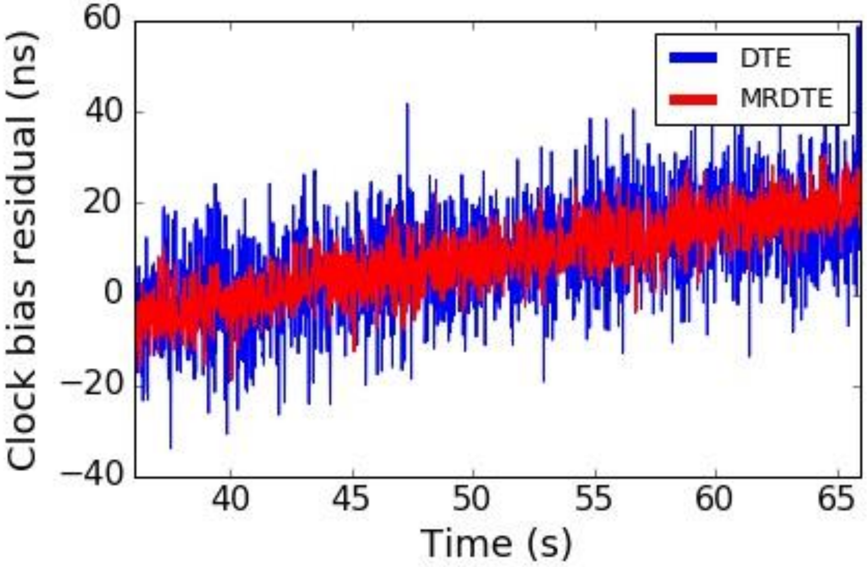

**Clock drift**



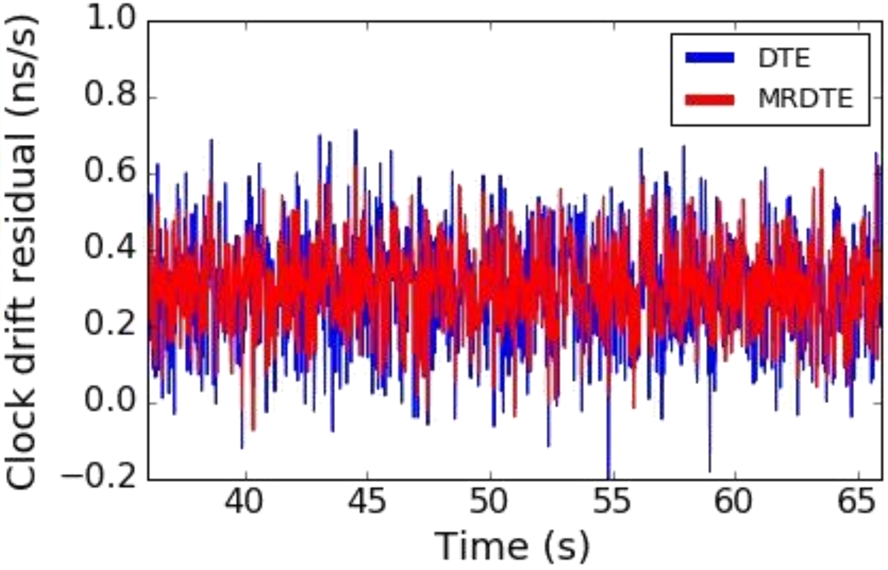

At $12dB$ jamming, MRDTE maintains a residual in clock bias of $< 100ns$ and clock drift of $< 1.5ns/s$

# Jamming: Single vs Multiple

### Clock bias

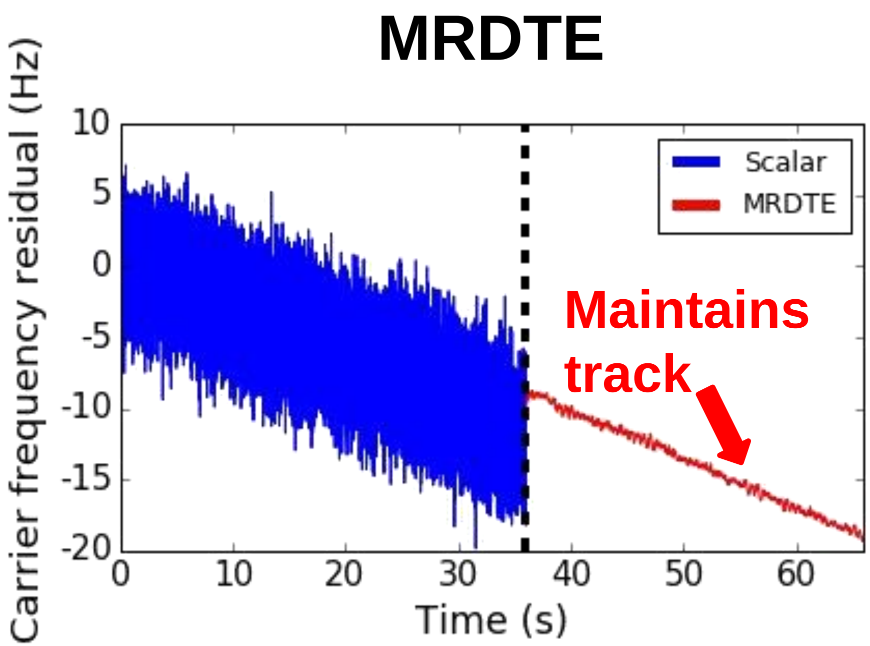


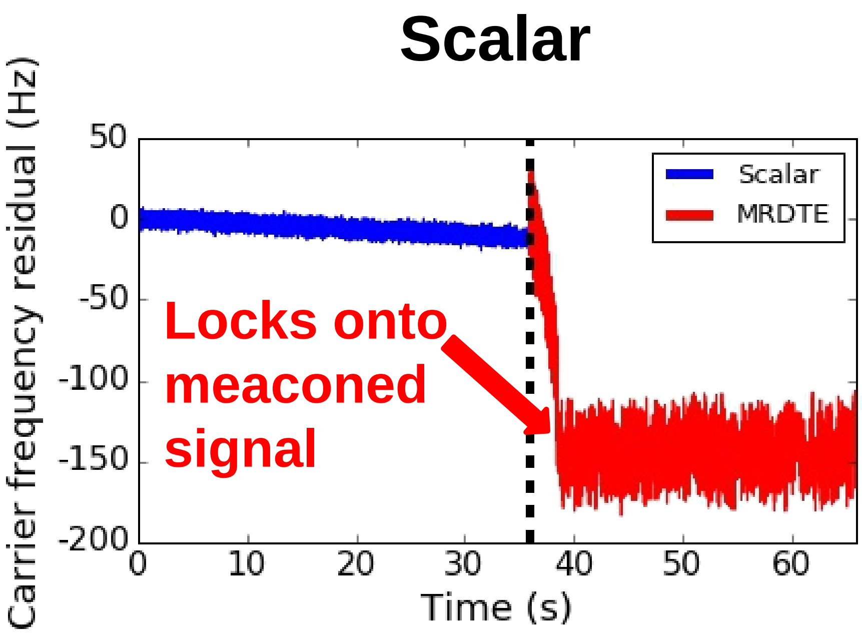

### Clock drift




Multiple receivers show smaller variance in the clock bias as compared to single receiver

# Meaconing: Carrier Frequency




Scalar tracking is operational until **2dB** of added meaconed signal while MRDTE is operational till **5dB**

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# Ongoing Work

- Objective:
  - Comparison of the performance robustness of the MRDTE and Scalar tracking using RTDS setup

RTDS stability analyzed

Raw GPS signals

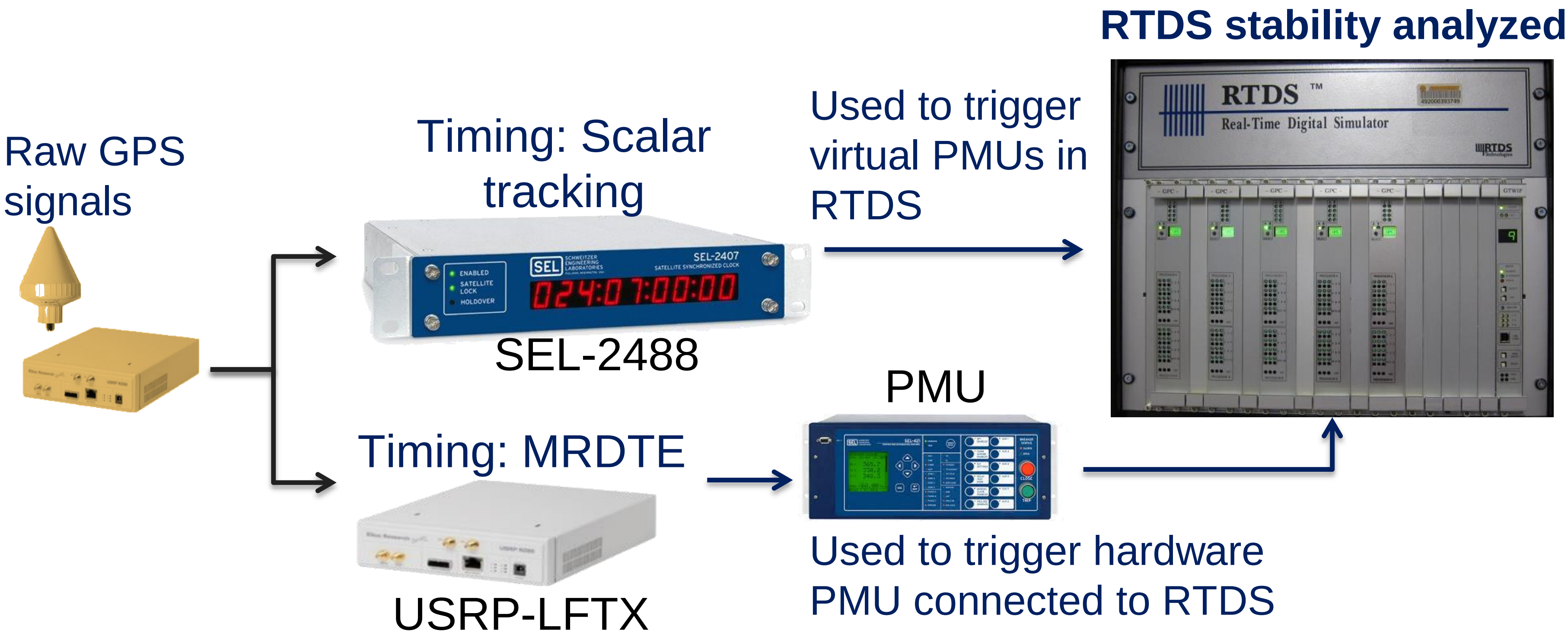
Timing: Scalar tracking


SEL-2488

Used to trigger virtual PMUs in RTDS

# Ongoing Work

- Raw GPS signals are supplied to SEL-2488 (external clock) to trigger virtual PMU and the hardware PMU is triggered using our MRDTE algorithm.

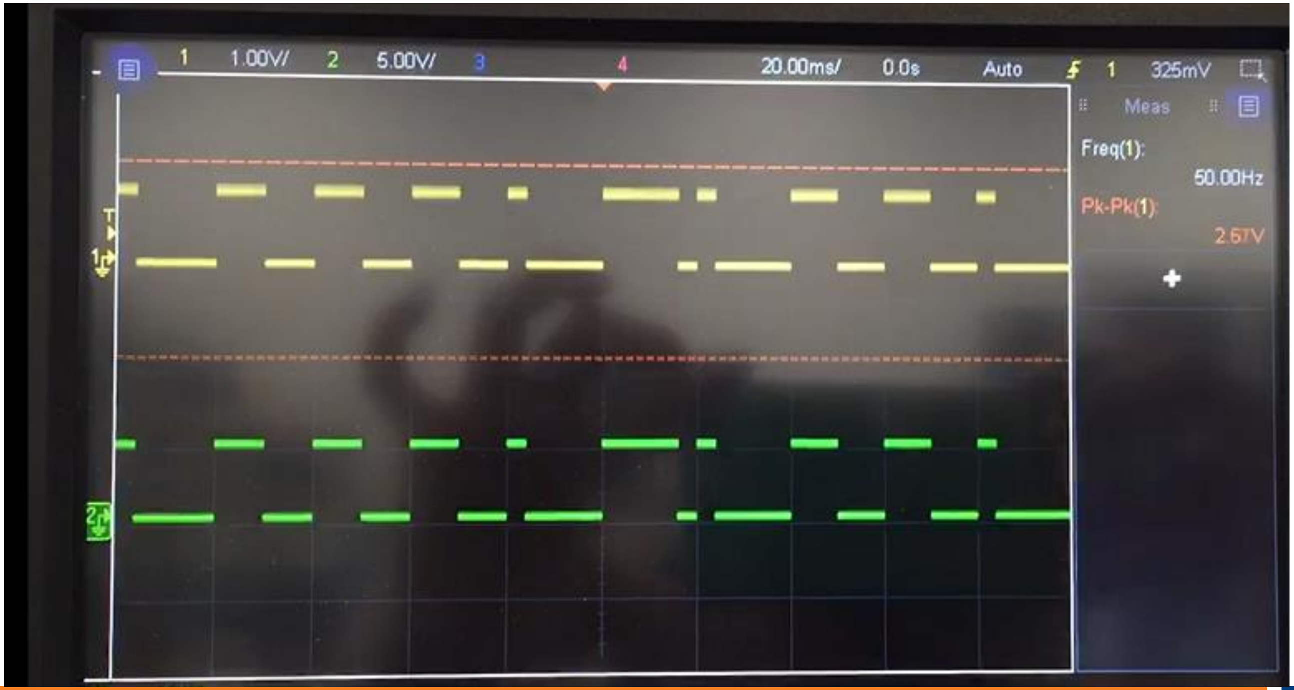


# Work done till now

- Generated the IRIG-B000 timing pulse: Input to PMU
- Created a voltage shifter to convert the transmitted USRP-LFTX 0-1v IRIG-B signal to 0-5v IRIG-B000 signal

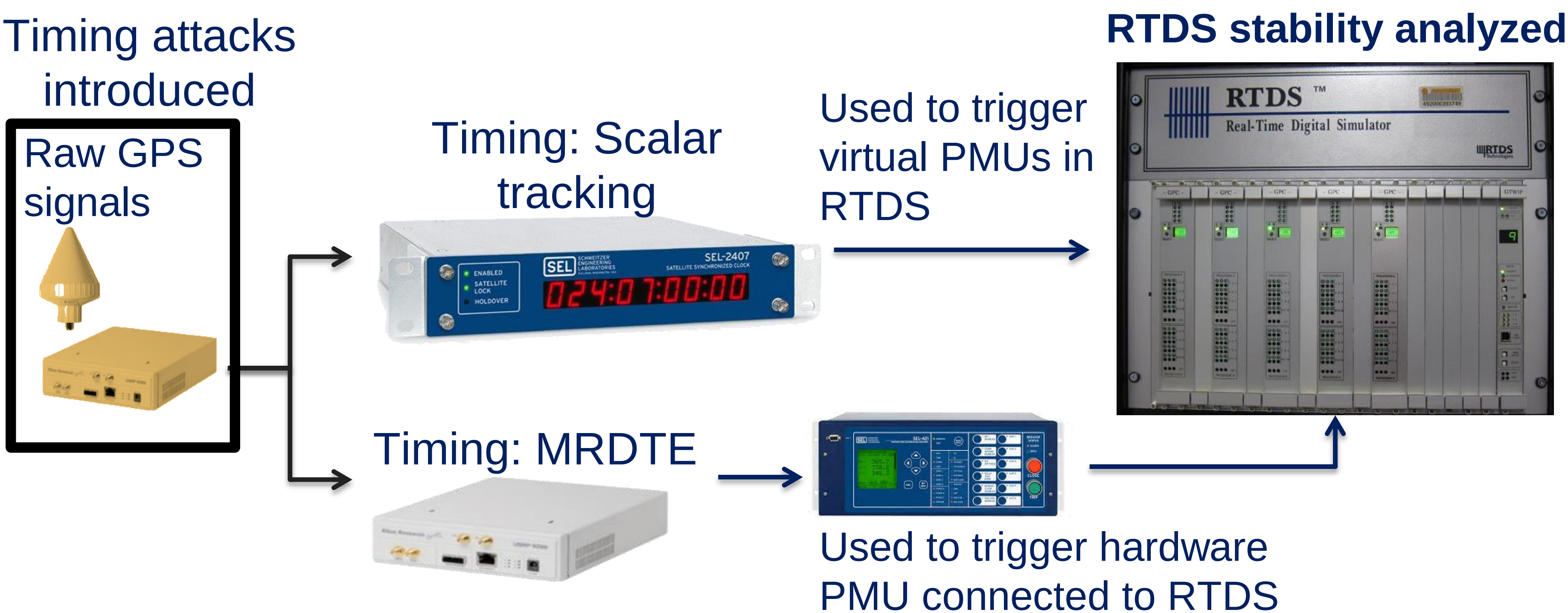
0-1v
IRIG-B000

0-5v
IRIG-B000



# Upcoming Work

- Timing attacks are simulated and added to the raw GPS signals being supplied to the SEL-2488 and USRP-LFTX.



# Summary

- Proposed a novel Multi-Receiver Direct Time Estimation (MRDTE) algorithm

- Verified the increased noise tolerance and successful mitigation of meaconing attack

| Timing Attack | MRDTE | Scalar |
|---|---|---|
| Jamming | **17dB** | 12dB |
| Meaconing | **5dB** | 2dB |

- Work being done in evaluating the impact of the MRDTE on power grid

# Thank You

Special Thanks to:

Prosper and Jeremy for helping with the experimental setup of power grid and in carrying out the evaluations

Acknowledgements:

This material is based upon work supported by the Department of Energy under Award Number DE-OE000078