Millisecond
Microsecond
Nanosecond

What Can We Do With More-Precise Time?

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Satisfying the Need for Time

"The only reason for time is so that everything doesn't happen at once."

– Albert Einstein

- 1845 USNO "Time Ball" noon daily
- Local "steam whistles"
- Time pulses over telegraph systems
- BBC "six pips" – 1924
- WWV time pulses – 1944
- WWVB 60 kHz – 1963

Fantastic Time Sources Today

Atomic Clocks

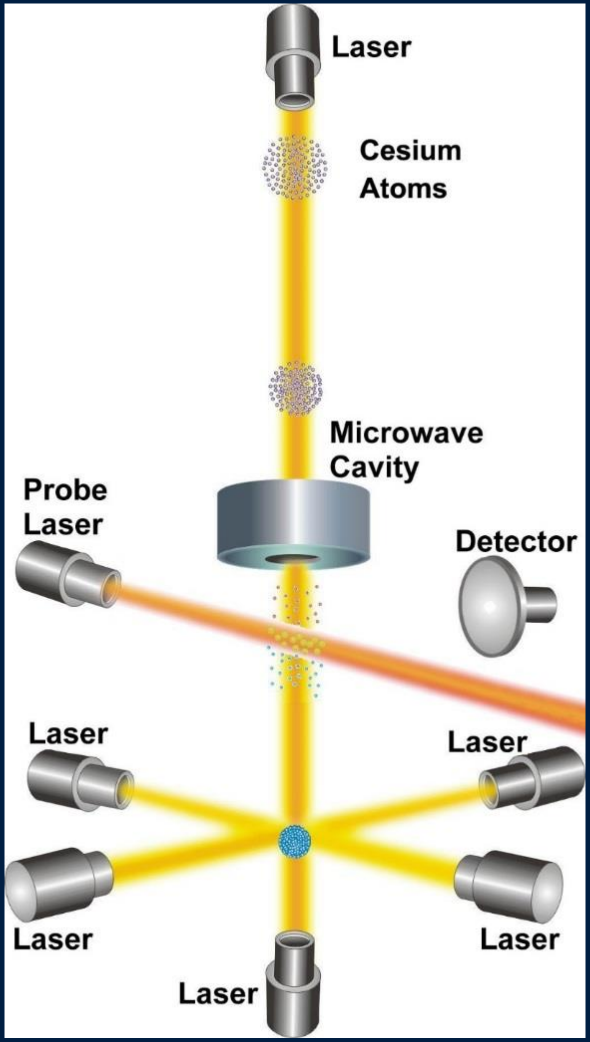


Image courtesy of NIST

GNSS

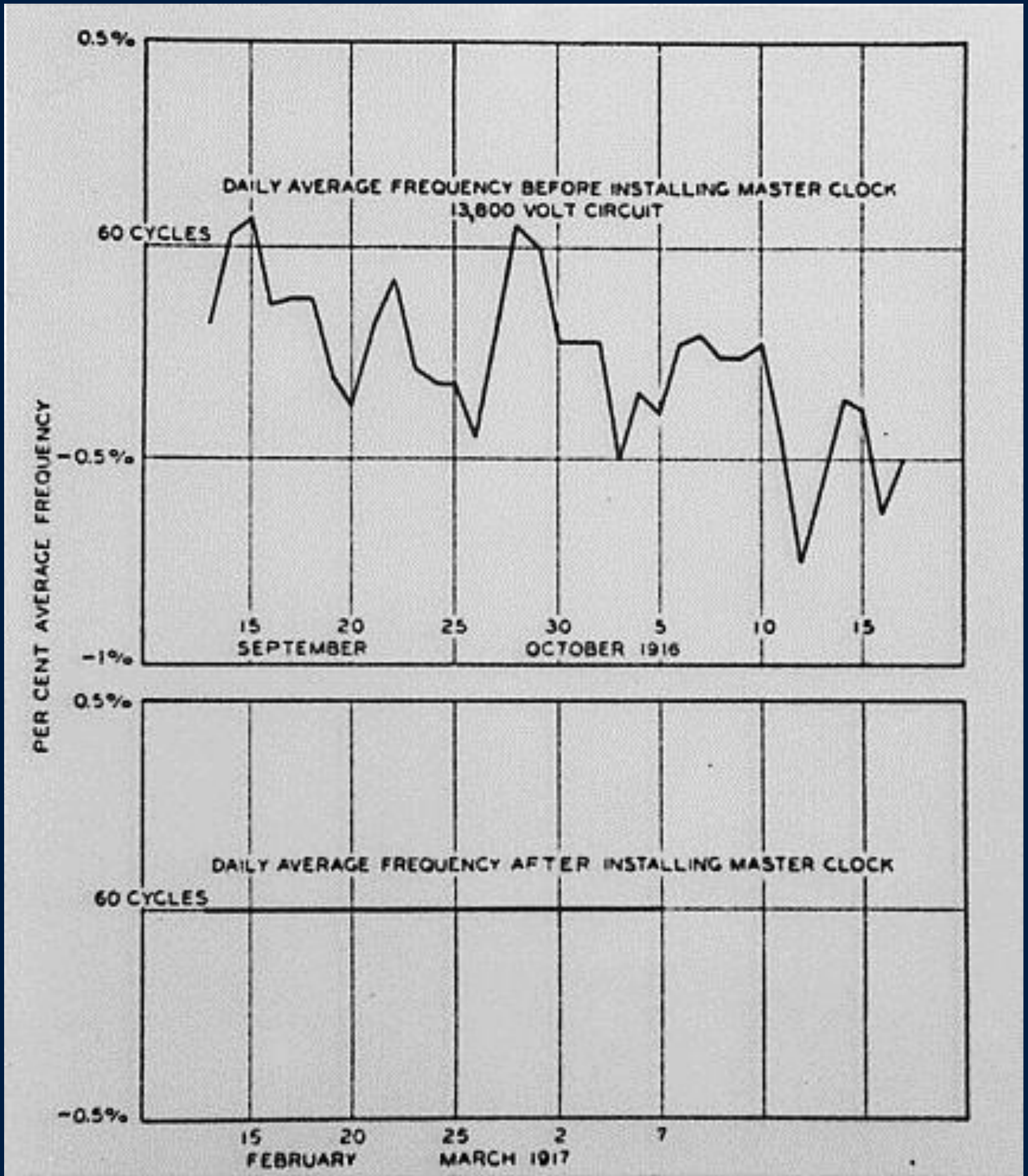
And, eLORAN at 100 kHz is emerging

Nanosecond time, anywhere

Time Distribution Methods
Utilities Sell Energy *and* Time

- *Synchronous-motor clocks* followed the power system, but the power system didn't follow any clock…until…
- Henry Warren of *GE Telechron* introduced the ***Master Clock*** in 1916
- AC power became a ***time reference***

Warren's Clock Controls Frequency



IRIG-B Time Code

Inter-Range Instrumentation Group, 1960

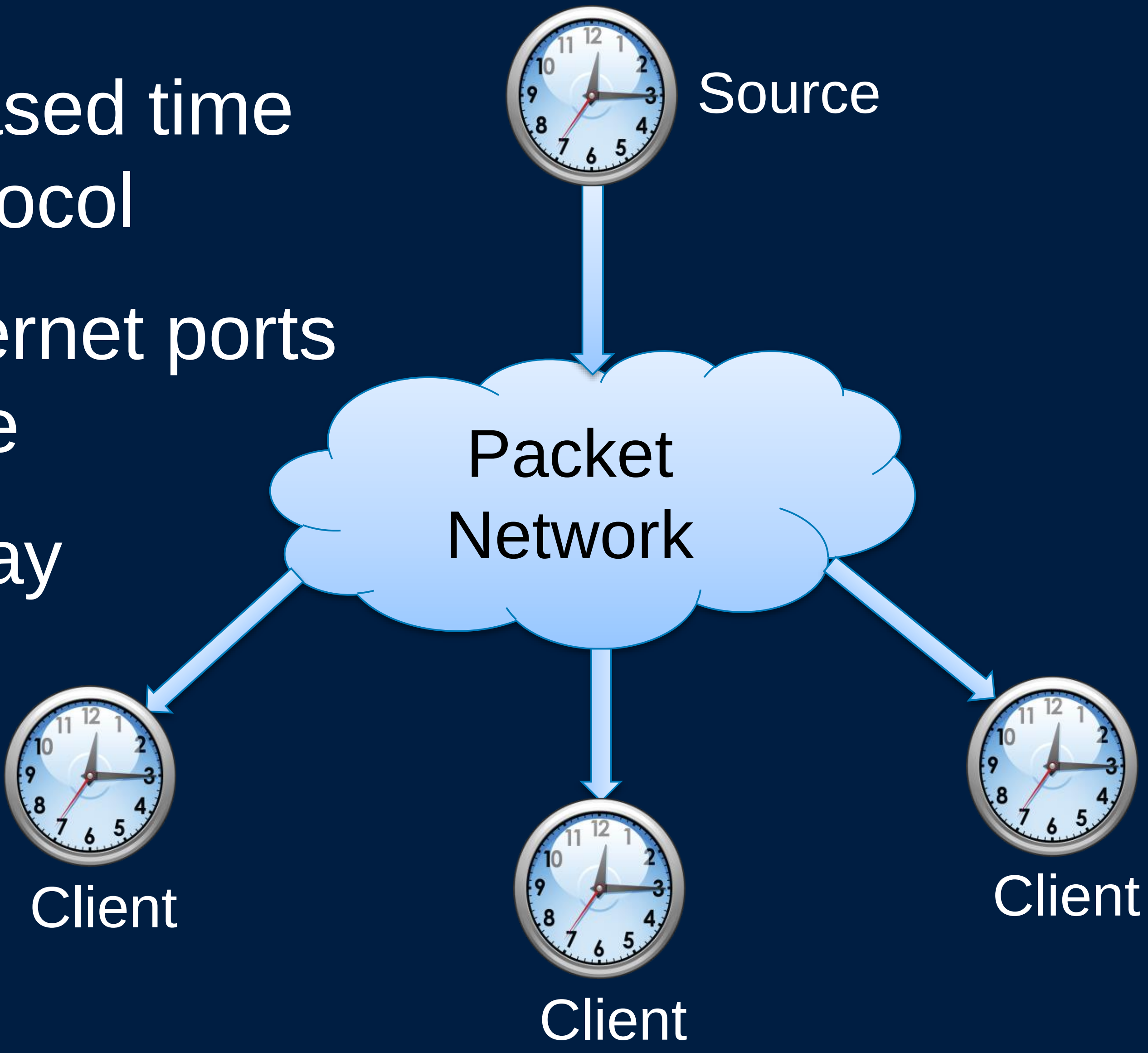
- 1 kHz carrier, 100 pps code
- Can see and decode on an oscilloscope
- Distribute over wire, cable, radio, ...
- “Demodulated” version: sharp edges on every 10 ms time mark
- Nanosecond-accurate edges
- Easy to compensate for cable delays

IRIG-B: Millisecond Pulses, Nanosecond Edges

One positive edge every 10 ms, "to the nanosecond"

PTP: Precision Time Protocol

- Message-based time transfer protocol
- Special Ethernet ports and software
- Accuracy may depend on network design

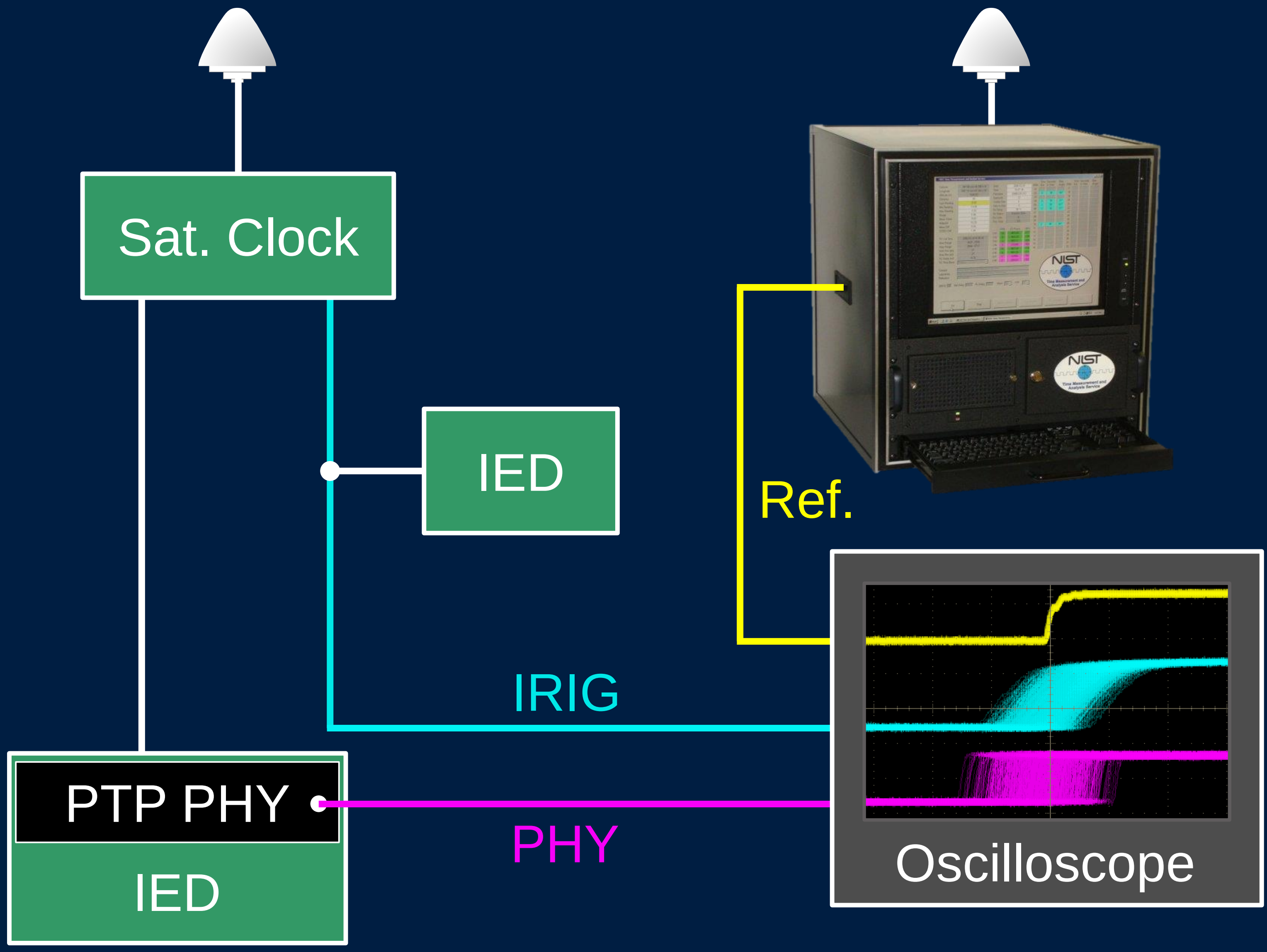


PTP Characteristics

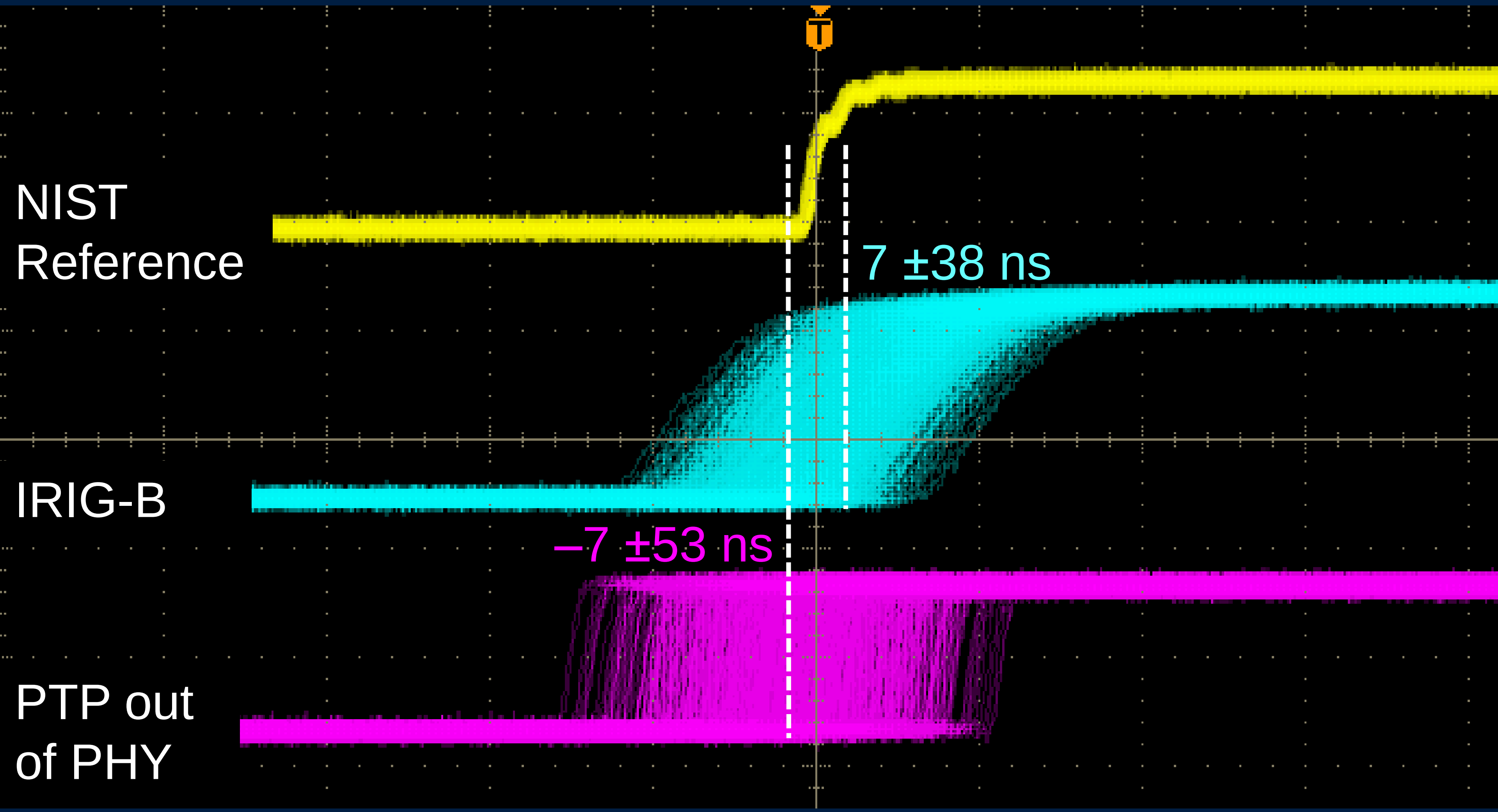
Precision Time Protocol (IEEE 1588), 2002

- Optimized for Ethernet
- Synchronizes clocks by *measuring* delays
- Special PTP switches required
- Characterizing performance requires advanced testing

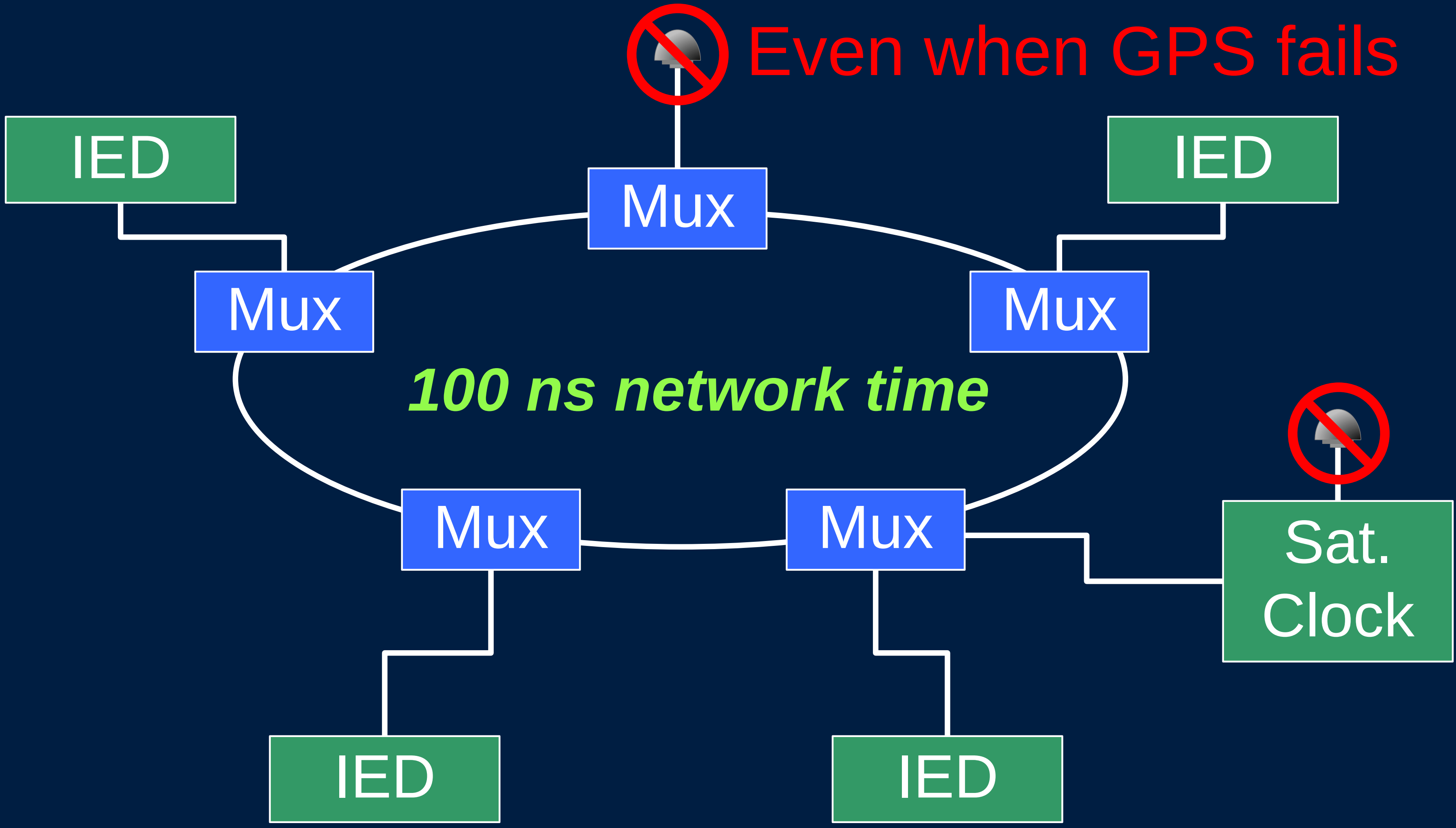
IRIG-B vs PTP Lab Tests



With Dedicated Switch, PTP ≈ IRIG-B



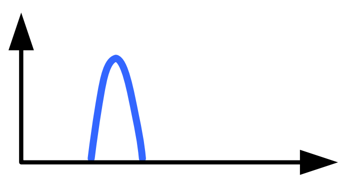
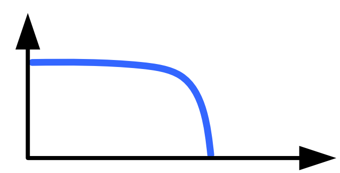
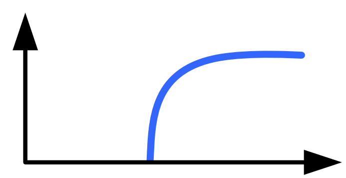
Synchronous Communications *and* Precise Time - SONET



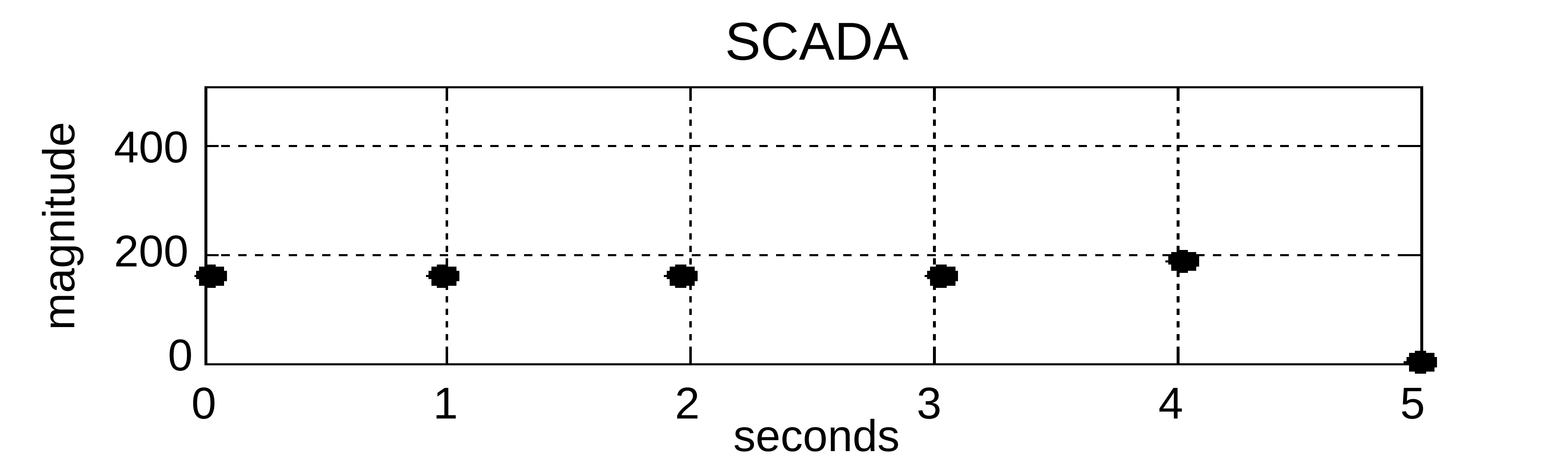
Milliseconds — *Phasors*

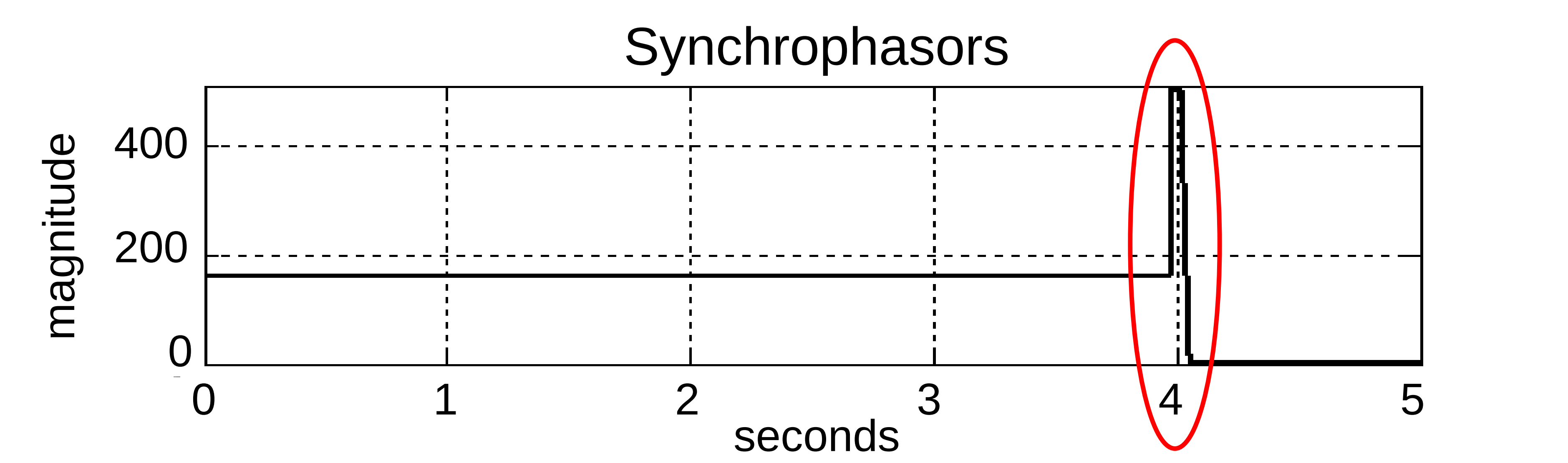
Microseconds — *Incremental Quantities*

Nanoseconds — *Traveling Waves*

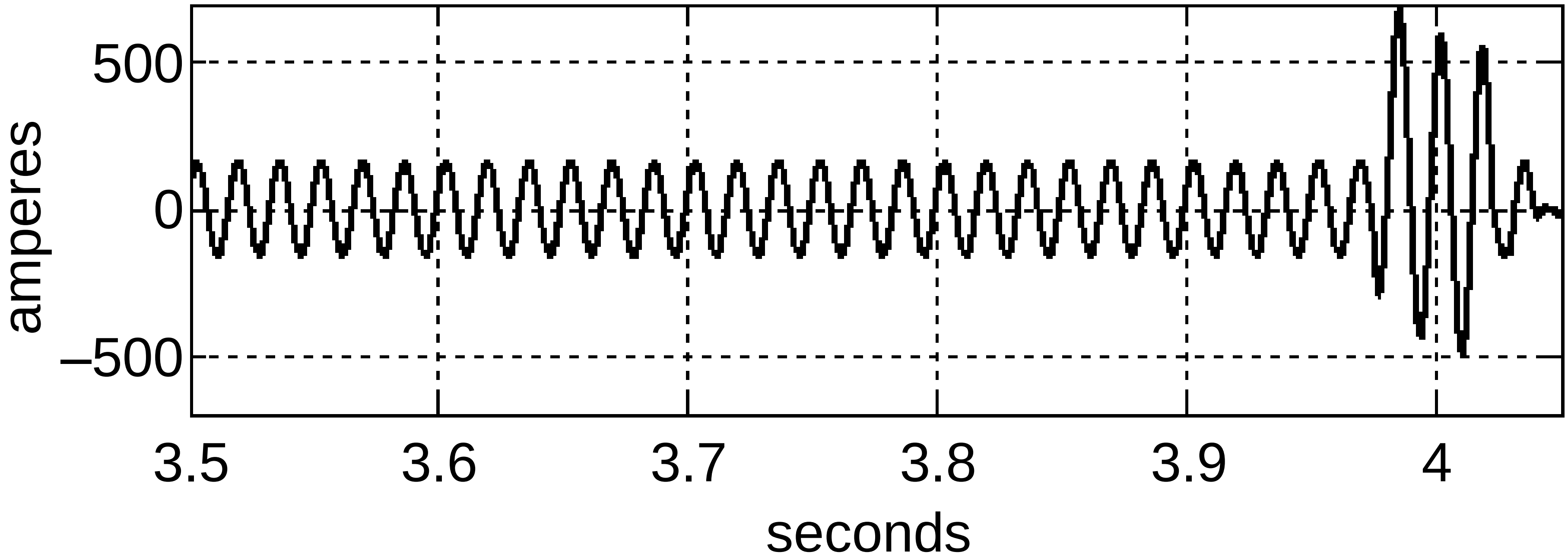
Technology	Phasors	Incremental Quantities	Traveling Waves
Spectrum	50 / 60 Hz	1 kHz	> 100 kHz
Filtering			
Sampling	16–32 s/c	8 kHz	1 MHz
Line Theory	$V_F = V - ZI$	$v_F = \mathrm{v} - \left(Ri + L\frac{di}{dt}\right)$	$i_{S(t)} \approx -i_{R(t-\tau)}$

Synchrophasors: One degree ≈ 46 μs

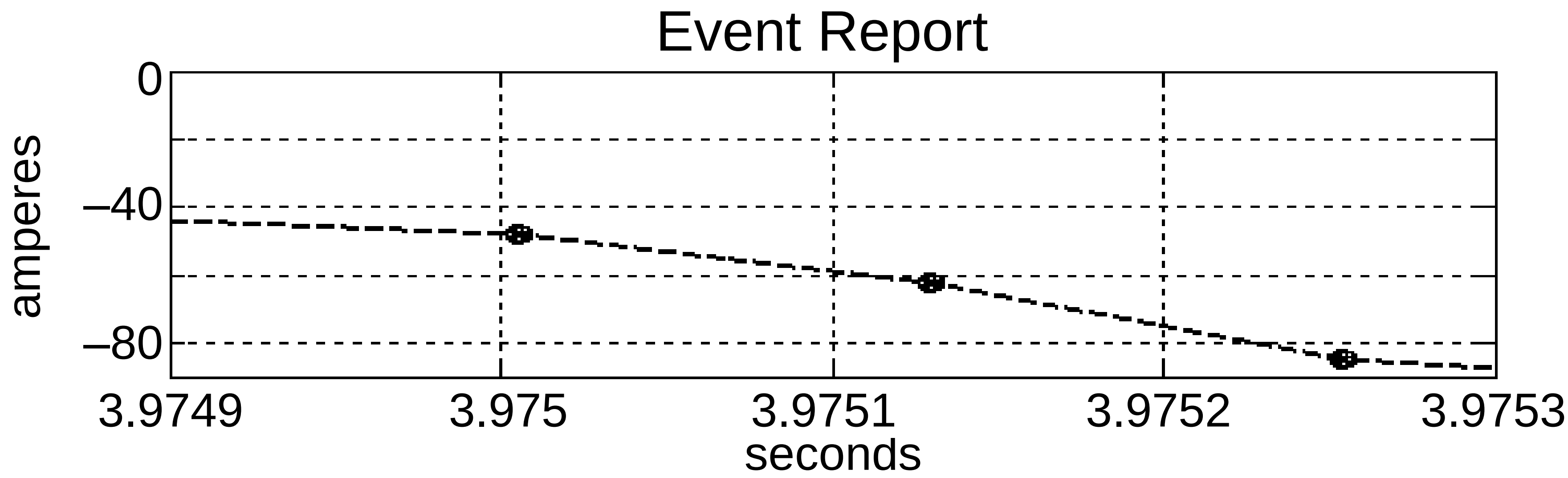


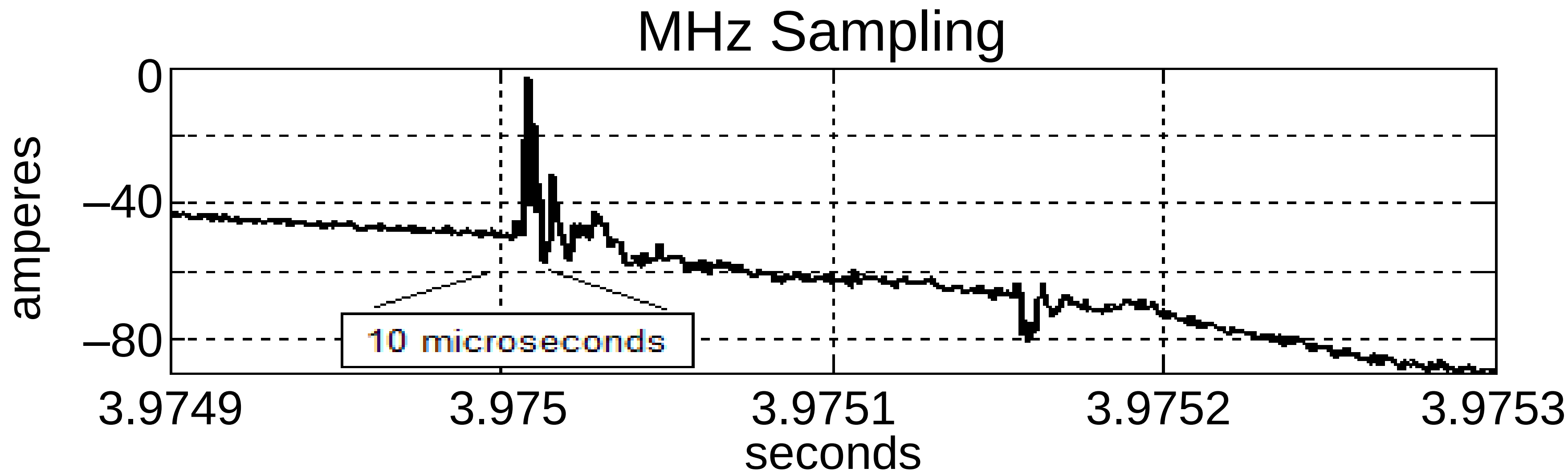


Time Domain Shows Exponential Offsets, CCVT Transients, …

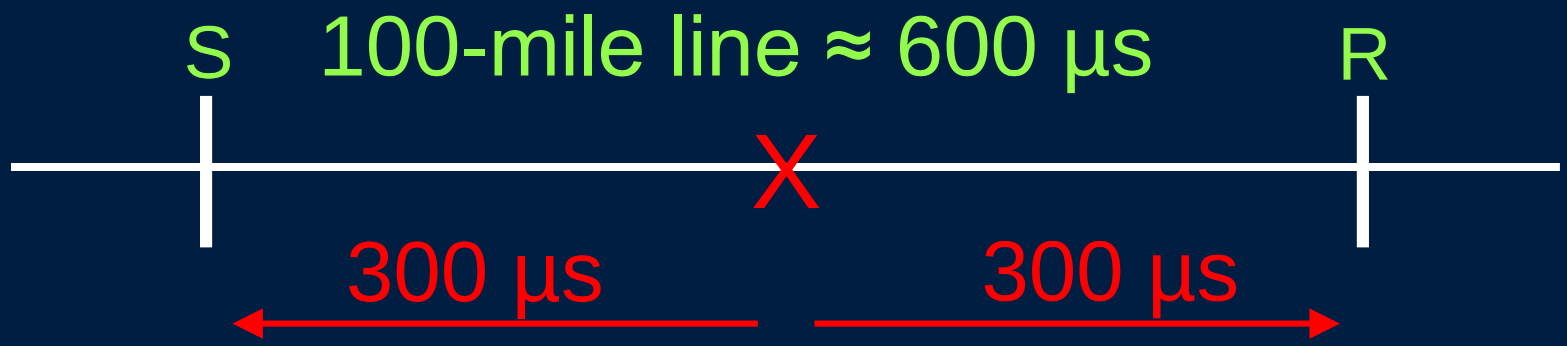


Megahertz Sampling Reveals Traveling Waves





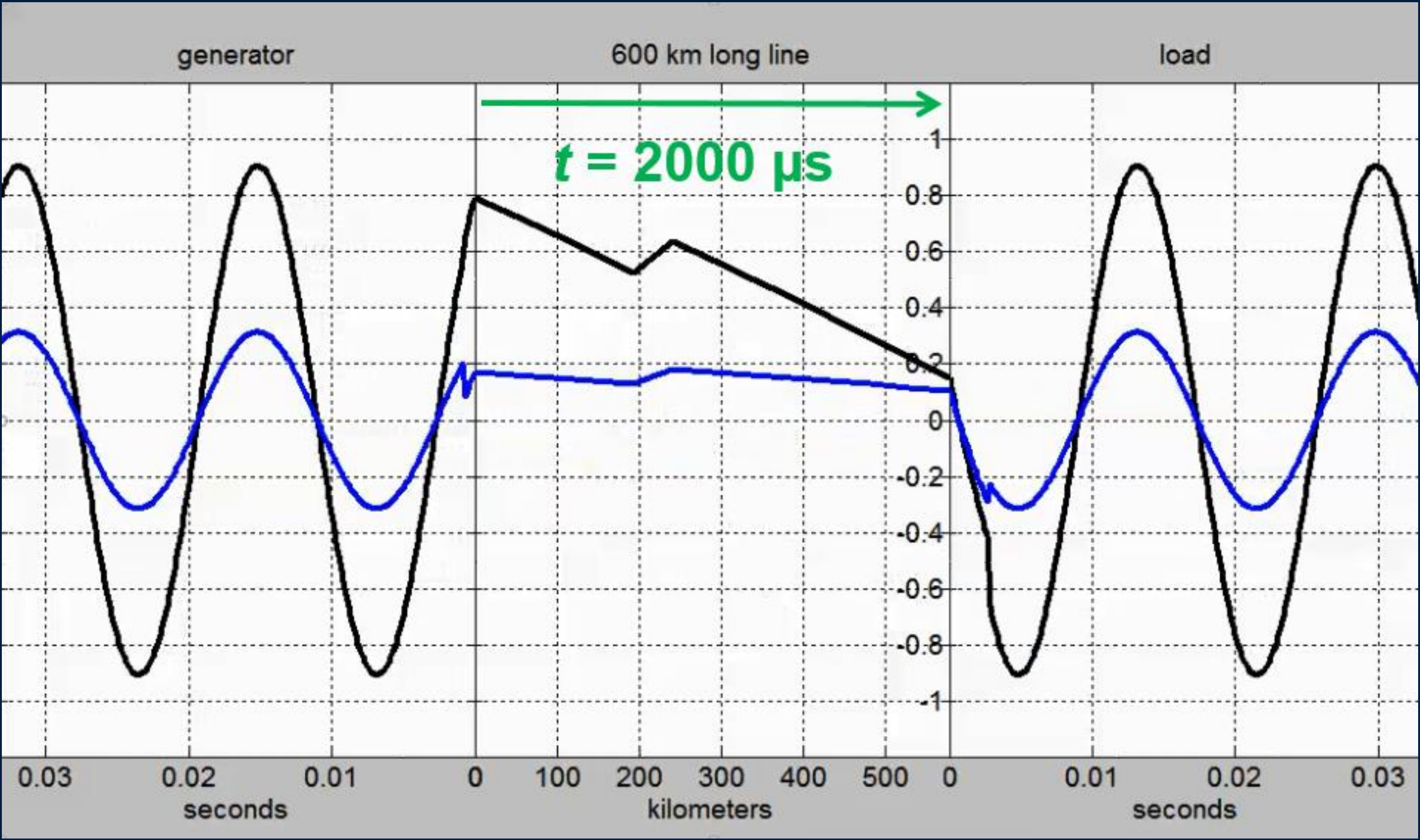
T = 0 Is When the Network Changes



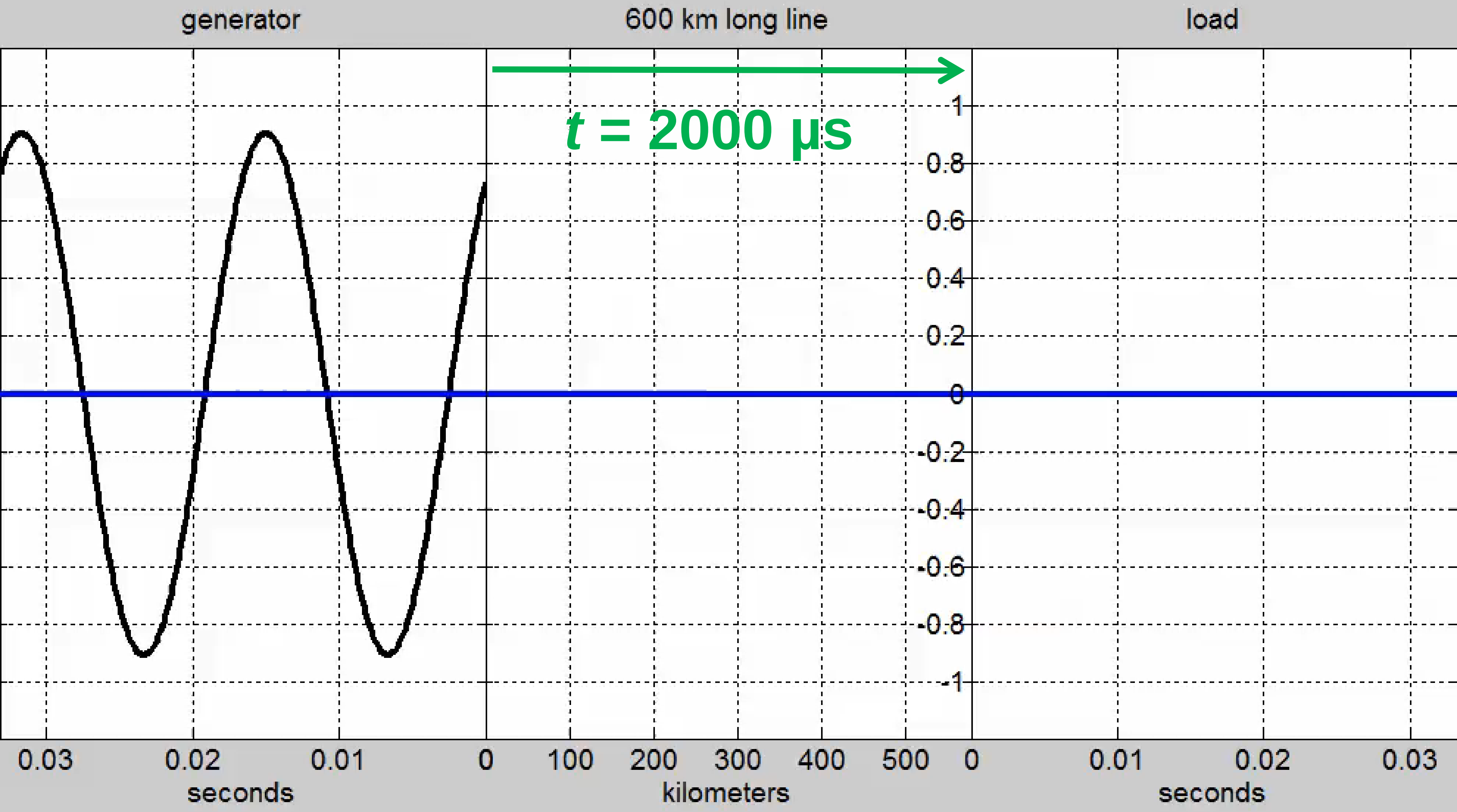
µs: Waves travel from the fault, and bounce back and forth, until the network settles into a new steady state.

Phasors: A fault happens, and sources behind S and R push current thru the fault… the same steady state.

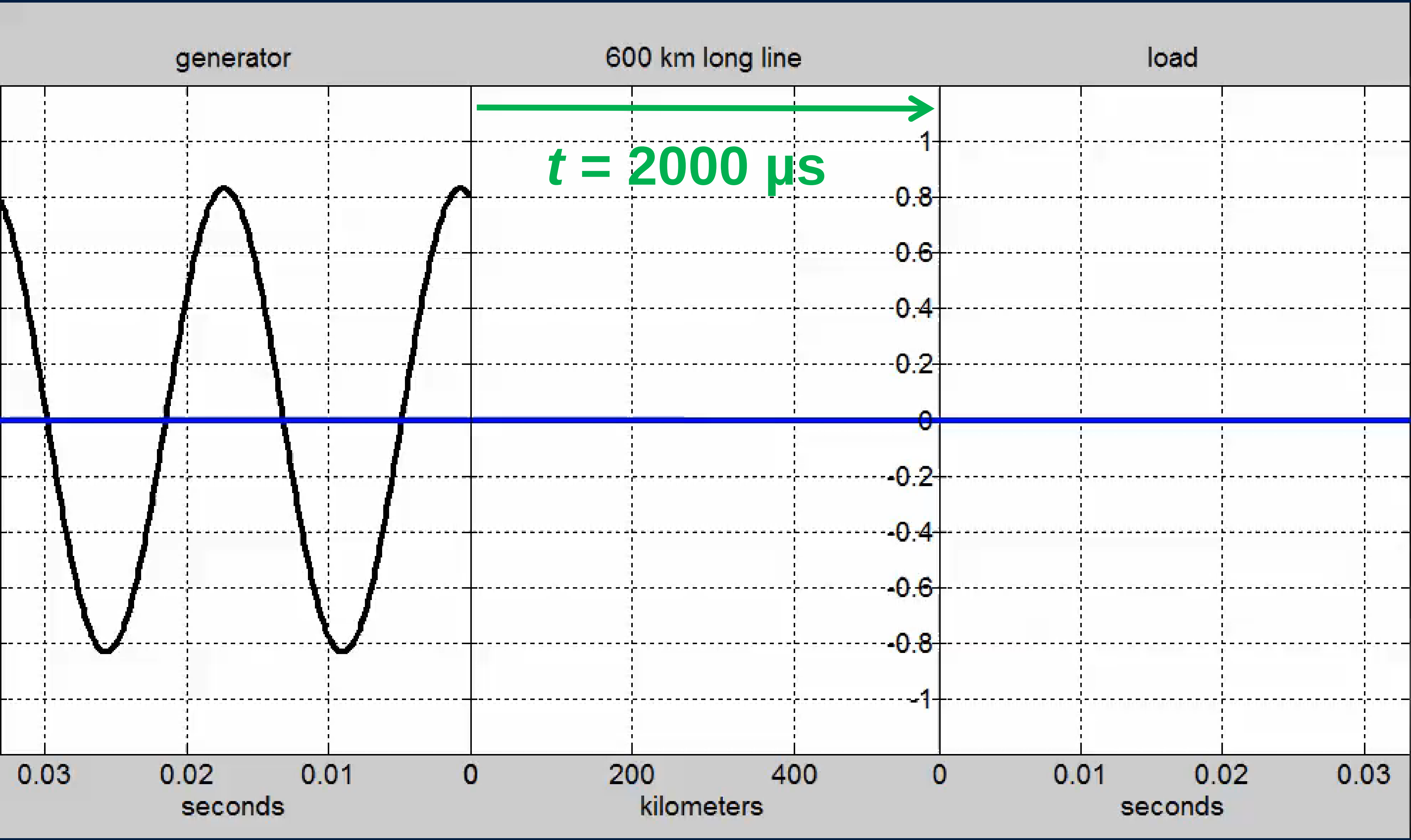
Energize Line, Then Pick Up Load



Energize Line, Then Pick Up Load



Energize Line, Pick Up Load, Fault



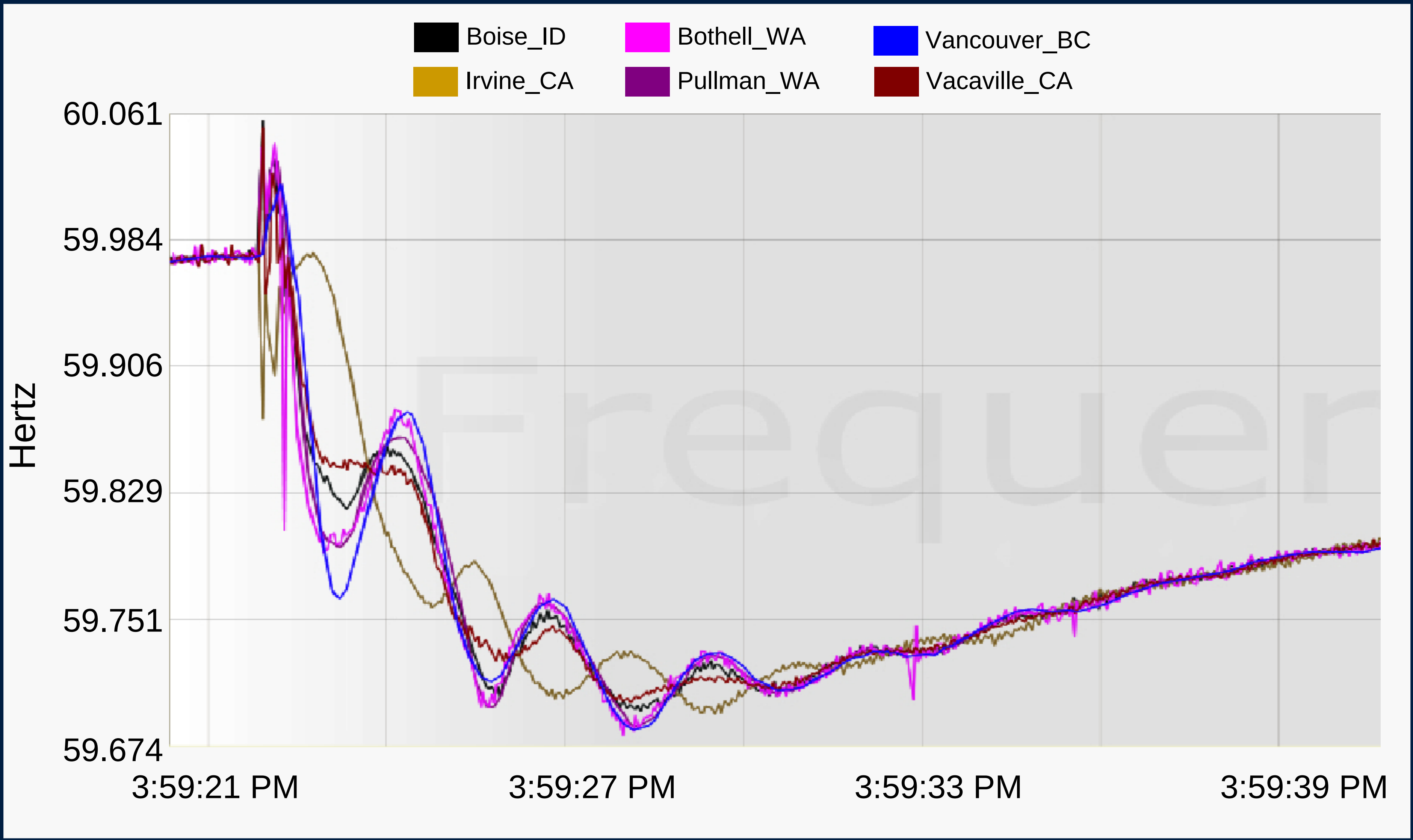
Time Domain Improves Wide-Area Analysis

Time Domain is *What's Happening*

Phasors imply *a Sinusoidal Steady State*

Subsynchronous oscillations	TD
System event analysis	TD => Phasors
Geomagnetic disturbances	TD => Phasors
Model validation	TD => Phasors
Situational awareness	TD => Phasors
Modal analysis	TD

Frequency Depends, Time Is Certain



Energy "Packets" Drive Dynamics

I don't need to determine "frequency"

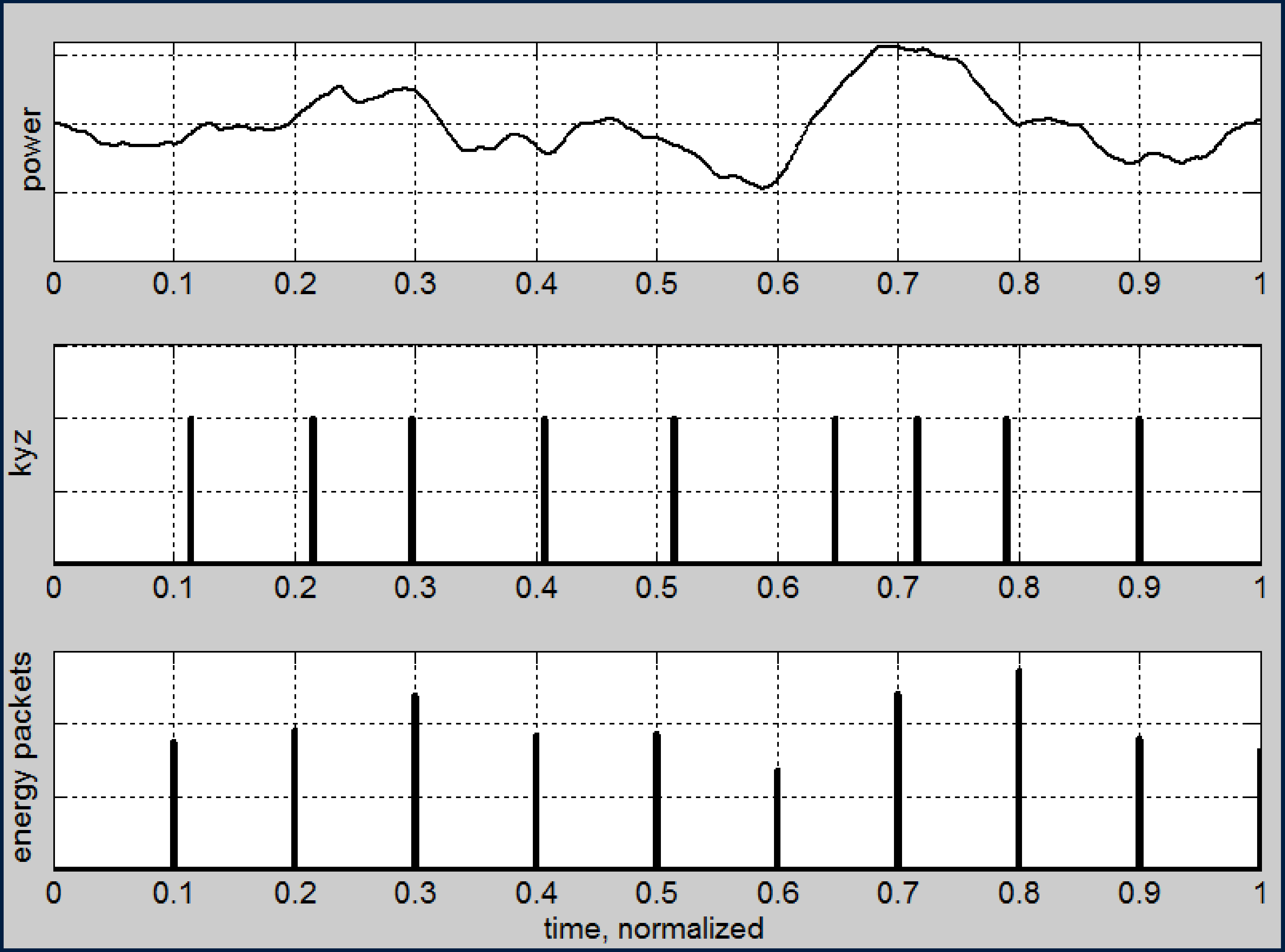
Average power depends on frequency

$$P_{average} = \frac{1}{1/f} \int_{t_k - 1/f}^{t_k} v(\tau) i(\tau) d\tau$$

Energy packets depend on time

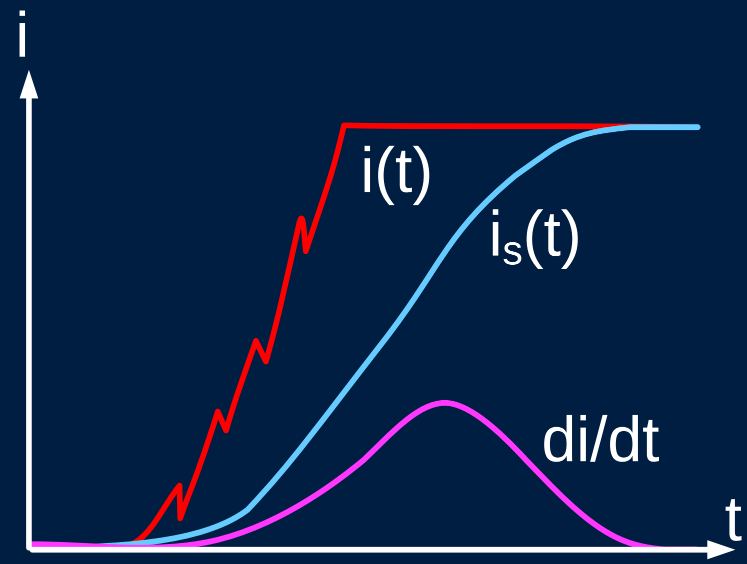
$$E_{packet} = \int_{t_k - \mathrm{T}}^{t_k} v(\tau) i(\tau) d\tau$$

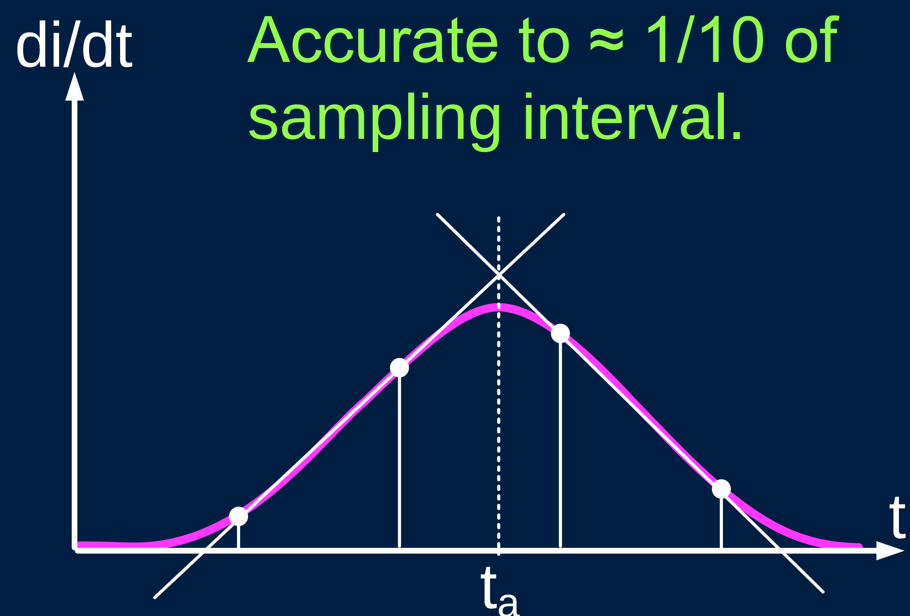
Synchronized Energy Measurements Make Real-Time Dynamics Easier



Traveling Wave Fault Location

Borrowed Idea From "Leading Edge Tracking"

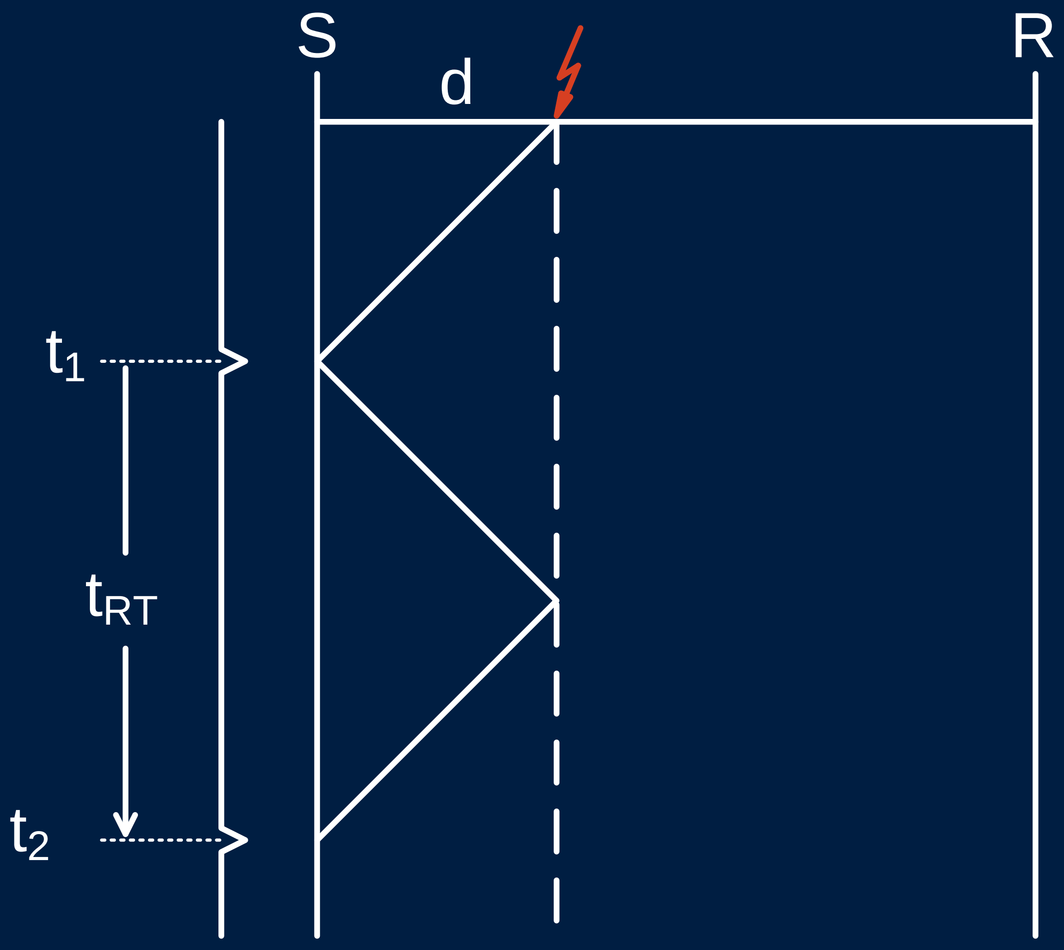




One End, Relative Time

$$d = \frac{t_2 - t_1}{2c}$$

t_2, t_1 are measured "to the nanosecond" by the same clock in the same instrument



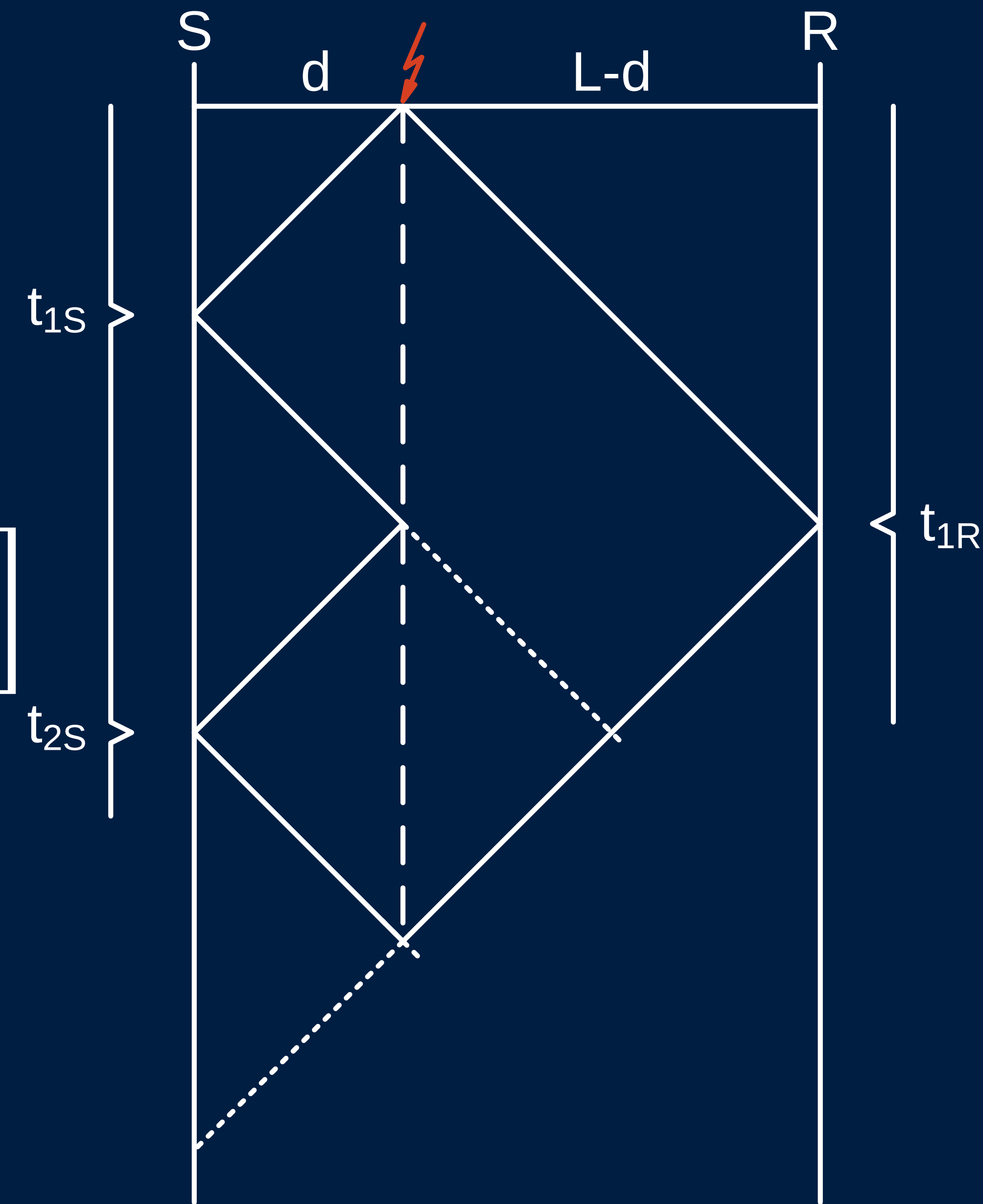
Two Ends, Need Synchronized Time

$$d = \frac{t_{1s}}{c} \qquad L - d = \frac{t_{1R}}{c}$$

$$\Sigma:\ \ L = \frac{t_{1s} + t_{1R}}{c}$$

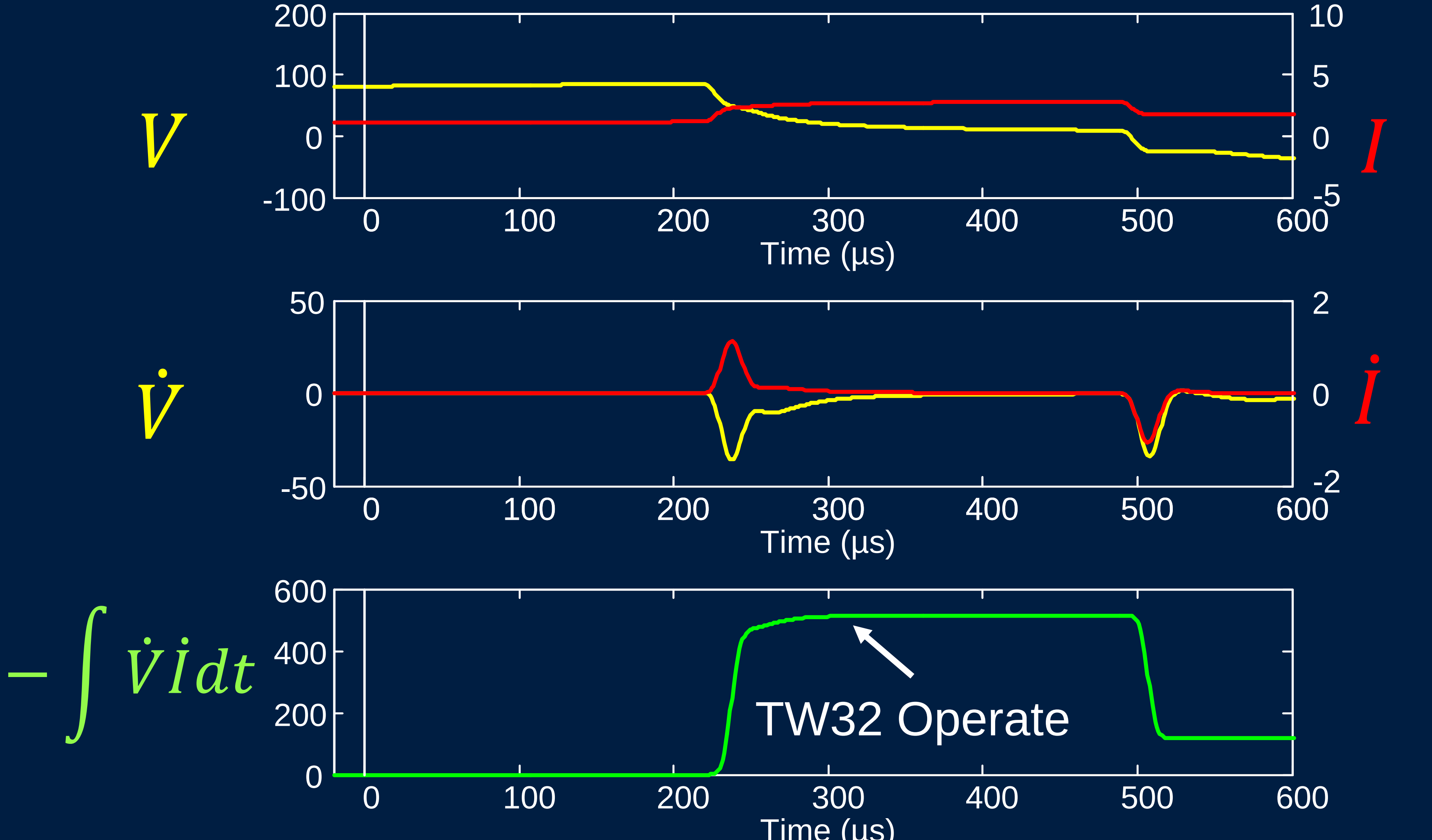
$$\Delta:\ \ d = \frac{1}{2}\left[L + \frac{t_{1s} - t_{1R}}{c}\right]$$

Relative: via channel
Absolute: external clocks



TW Directional Element

Microsecond Sampling, Submillisecond Direction



From Milliseconds to Nanoseconds

40 ns, 40 feet

- Frequency is variable. Time is absolute.
- Synchrophasors will give way to wide-area time-domain sampling.
- *Reliable absolute time to 40 ns* is practical.
- *Microsecond sampling with nanosecond accuracies* is leading to faster protection, better control, and new understanding of electric power systems.

Satisfying the Need for Time

"The only reason for time is so that everything doesn't happen at once."

– Albert Einstein

- Microseconds happen at once, if you're looking in milliseconds.
- Nanoseconds happen at once, if you're looking in microseconds.
- We will learn more as we move from milliseconds, to microseconds, into nanoseconds.