Massively Deployed Sensors

A report on a project done for the Power Systems Engineering Research Center (PSerc)

North American SynchroPhasor Initiative Meeting
Scottsdale, AZ

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PSERC

Core purpose

Empowering minds to engineer the future electric energy system

Important issues

- **Pursuing, discovering and transferring knowledge**
- **Producing highly qualified and trained engineers**
- **Collaborating in all we do**

- **Arizona State University** - Gerald Heydt
- **University of California - Berkeley** - Shmuel Oren
- **Carnegie Mellon University** – Marija Ilic
- **Colorado School of Mines** - P.K. Sen
- **Cornell University** – Tim Mount
- **Georgia Institute of Technology** - Sakis Meliopoulos
- **Howard University** - James Momoh
- **University of Illinois at Urbana** - Peter Sauer
- **Iowa State University** - Jim McCalley
- **Texas A&M University** - Mladen Kezunovic
- **Washington State University** - Anjan Bose
- **University of Wisconsin-Madison** - Chris DeMarco
- **Wichita State University** - Ward Jewell

PSERC

P S e r c

A collaboratory of 13 universities and ~40 sponsors with a core budget of 3.5M$/y plus about 2.0 M$ in university matching funds

Industry members

ABB
American Electric Power
American Transmission
AREVA T&D
Arizona Public Service
Baltimore Gas & Electric
British Columbia Trans. Co.
Bonneville Power Admin.
California ISO
CenterPoint Energy
Duke Energy
Entergy
EPRI
Exelon
GE Energy
FirstEnergy
Institut de recherche d'Hydro-Québec (IREQ)
ISO New England

ITC Holdings
MidAmerican Energy
Midwest ISO
National Grid USA
National Rural Electric Coop. Assn.
New York ISO
New York Power Authority
Pacific Gas and Electric
PJM Interconnection
PowerWorld
Quanta Technology
Salt River Project
Siemens
Southern California Edison
Southern Company
TVA
Tri-State G&T
TXU Electric Delivery
U.S. DOE
Western Area Power Administration

Researchers

- 40 researchers
- Multidisciplinary, specializing in:
  - power systems, applied mathematics, non-linear systems, power electronics, control theory, computing, operations research, T&D, power markets
  - economics, industrial organization and public policy

Students

- Strong synergy between research and education
  - About 60 graduate students working on PSerc research projects
  - Research improves quality of education experience
  - Research required of faculty
- Quality power programs (grad and undergrad)
- Employment search assistance

MORE INFORMATION AT WWW.PSerc.ORG

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PSerc 'Massively Deployed Sensors' project participants

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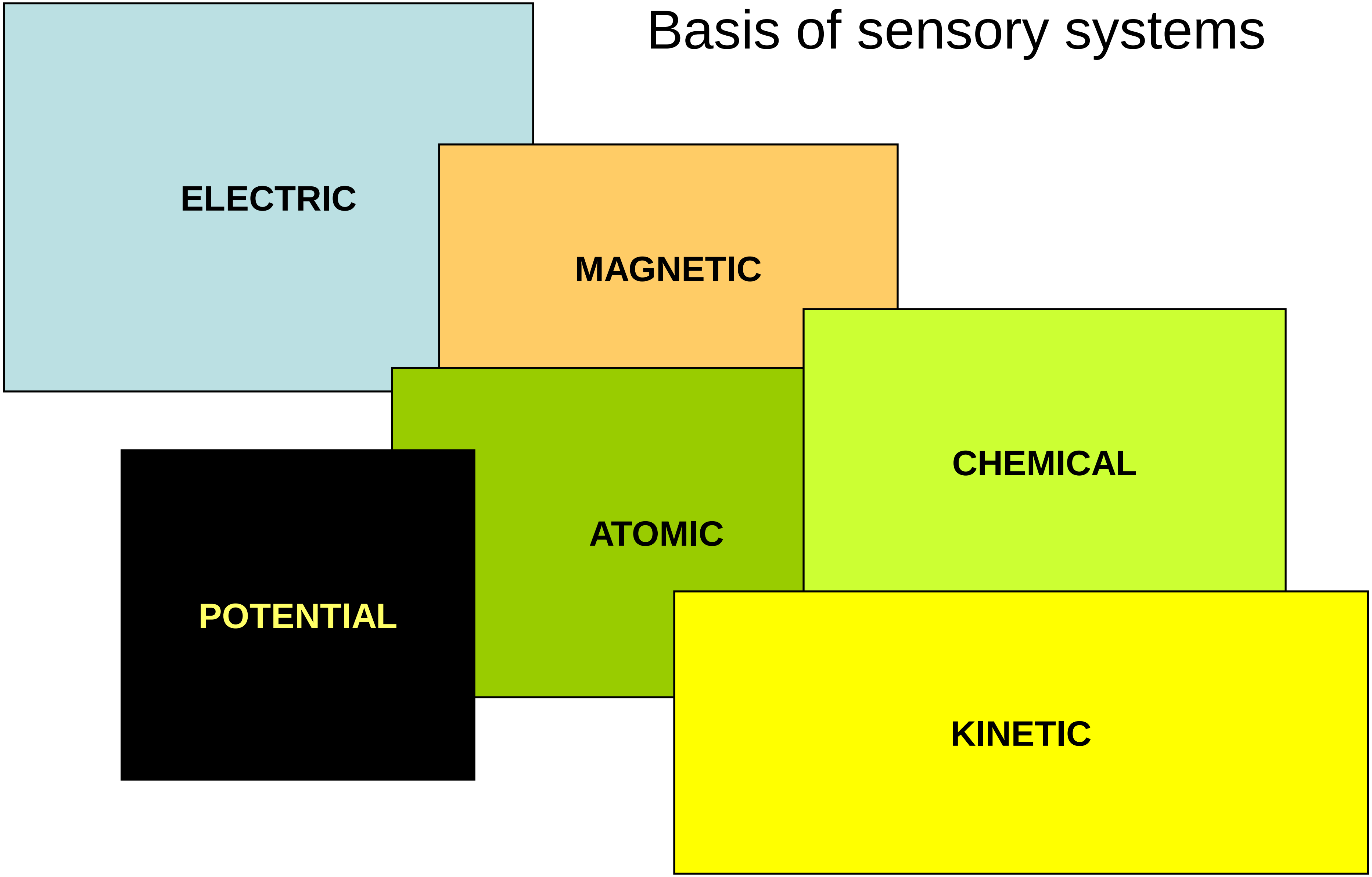
Web site: http://www.engr.wichita.edu/ces/sensors/

Main project elements

- **Integration of *existing* sensory information from sensors (e.g. temperature and pressure, substation security perimeter status, substation battery voltage, neutral - ground voltage, liquid levels) into the EMS and alarm processing software tools.**
- **Investigation of *unconventional* sensors and sensory information (e.g., satellite graphic information, mechanical position and inclinometer-type sensors, static wire impedance, conduit and cable trough conductivity).**
- **Development of alarm processing techniques and algorithms that utilize a large number of sensory information sources including unconventional sensory information. The alarm processing techniques may use innovative mathematical techniques.**
- **The use of a very large number of signals for enhanced power system operation and operational decision making in order to capture new information and to enhance the accuracy, quality, and redundancy of the collected information. This includes, for example, analysis of data fusion, size and complexity of data, efficient power usage for sensors, optimal location of sensors with respect to chosen metrics, and availability of communication channels to transmit sensor data.**

Forms of energy

Basis of sensory systems



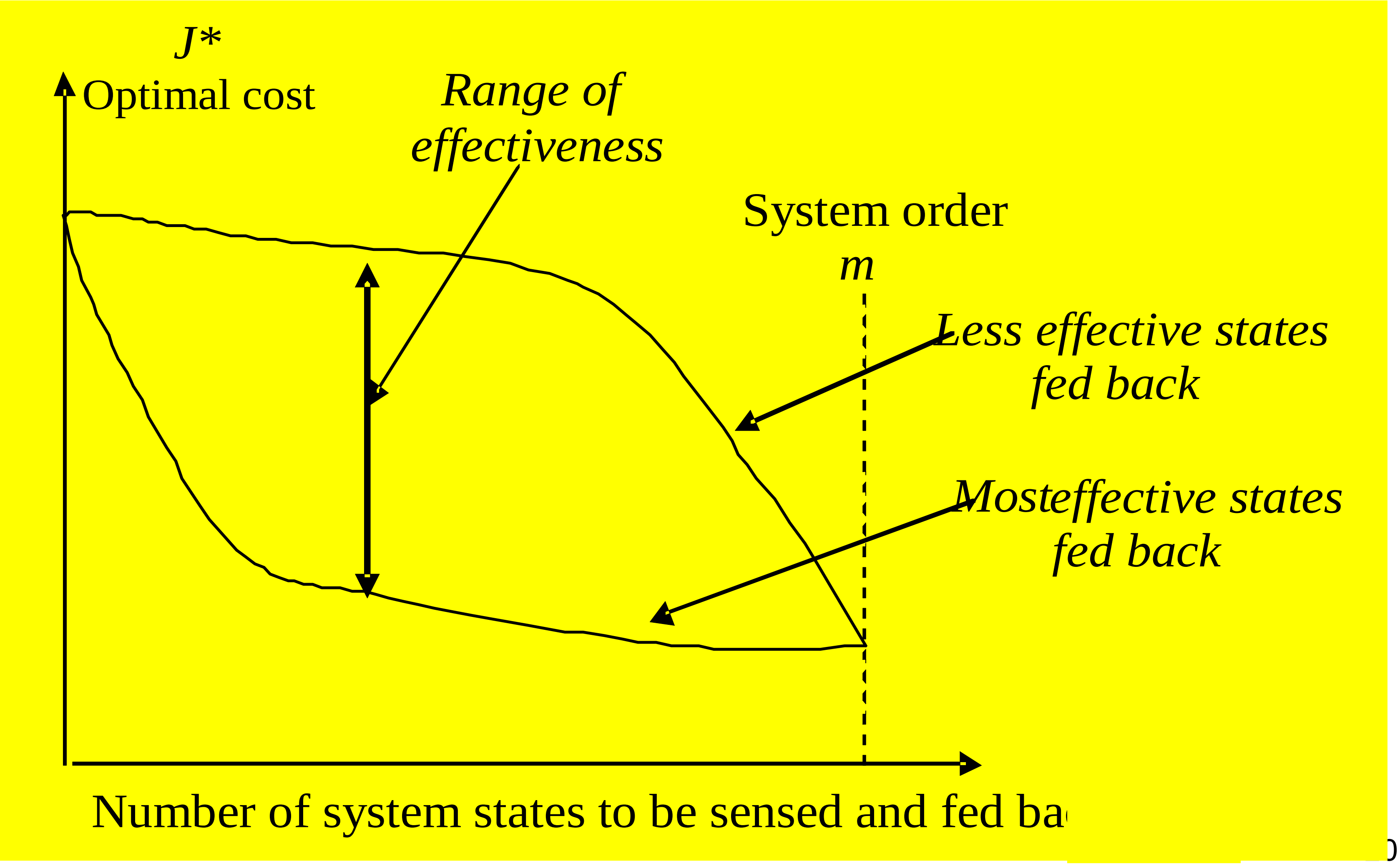
Potential sensory signals

Quantity	*Transmission Lines*	*Substations*	*Transformers*	*Circuit Breakers*
Acceleration	**X**			
Vibration	**X**	**X**	**X**	
Stress / Strain	**X**			
Tension	**X**			
Shock	**X**	**X**		
Pressure			**X**	
Temperature	**X**	**X**	**X**	**X**
Inclination / Tilt	**X**	**X**	**X**	
Position				**X**
Protective relay output	**X**	**X**	**X**	**X**

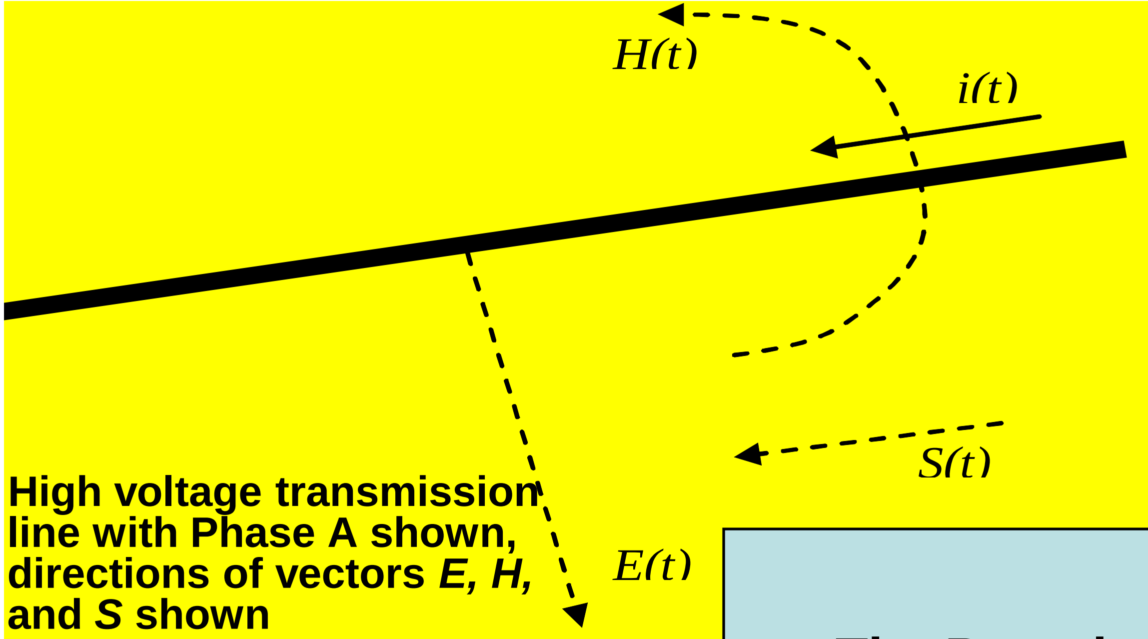
Bandwidth requirements

Wide, greater than 10 kHz					
Moderate, 6 - 10 kHz					
Intermediate, 3 to 6 kHz					
Narrow, less than 3 kHz					
Very narrow, less than 100 Hz					
BANDWIDTH	POWER TRANS-FORMER	REVENUE PT	RELAYING PT	FIELD INSTRUMENTATION APPLICATIONS PT	LABORATORY GRADE PT

Assessment of the optimal number of sensors to improve an index of quality, *J*



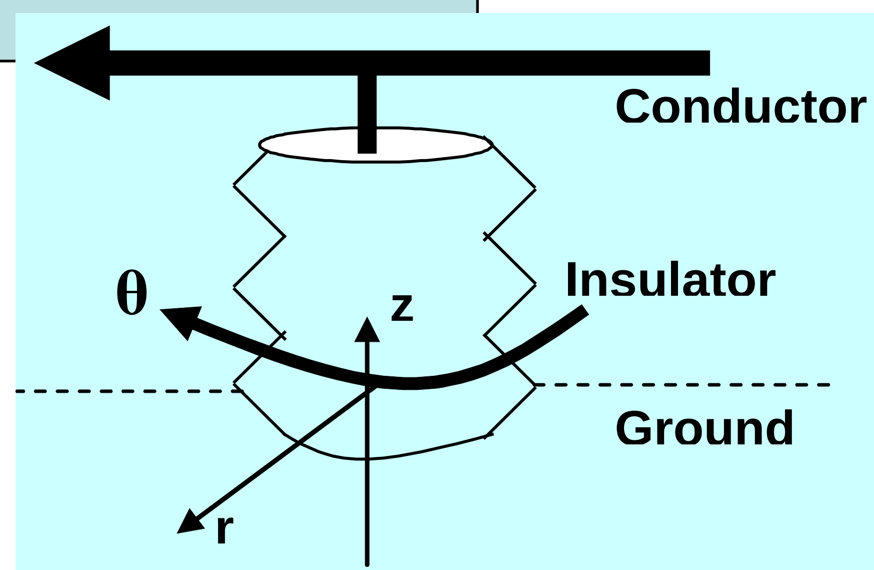
Some innovative sensors



The Poynting vector

$$S = [E] \times [H]$$

It may be possible to assess losses in a post type insulator by measuring the Poynting vector, *S*, and integrating this across a surrounding surface. This is the lost active power in the insulator.

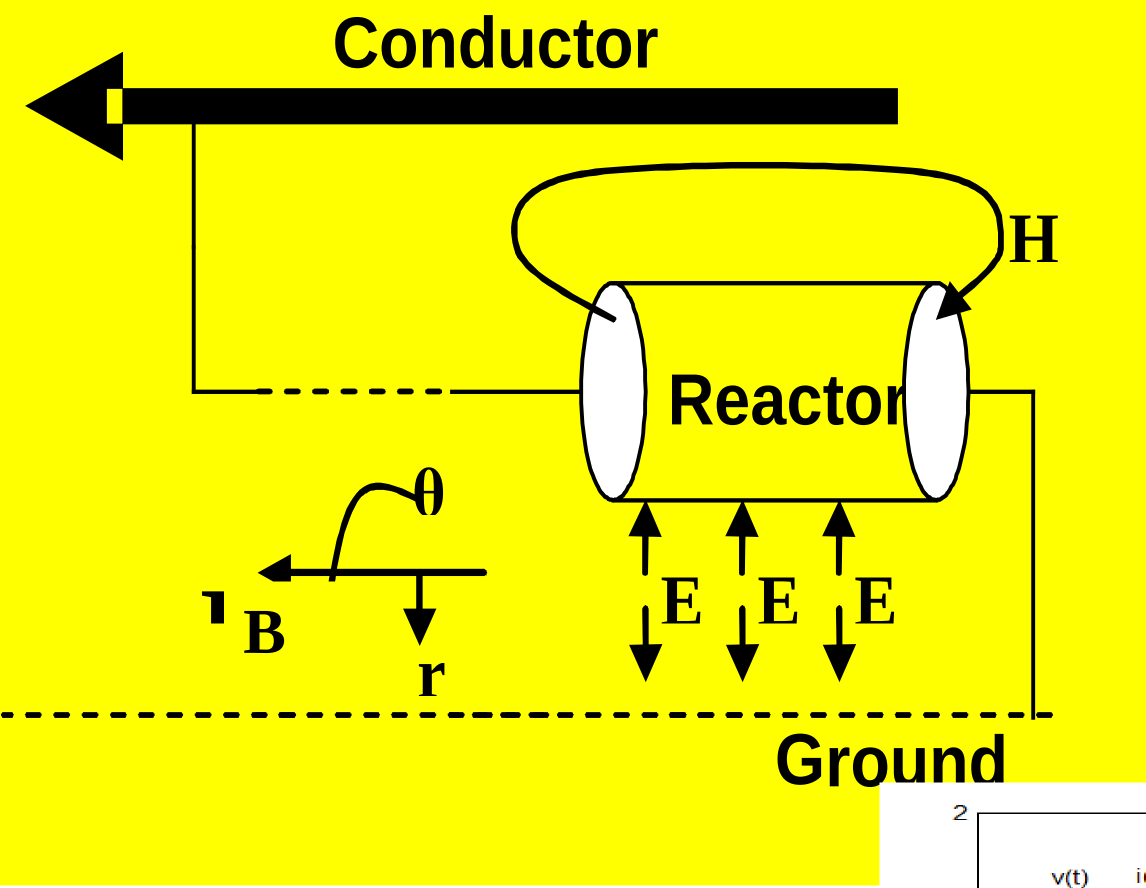


$$u \times v = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ u_x & u_y & u_z \\ v_x & v_y & v_z \end{vmatrix}$$

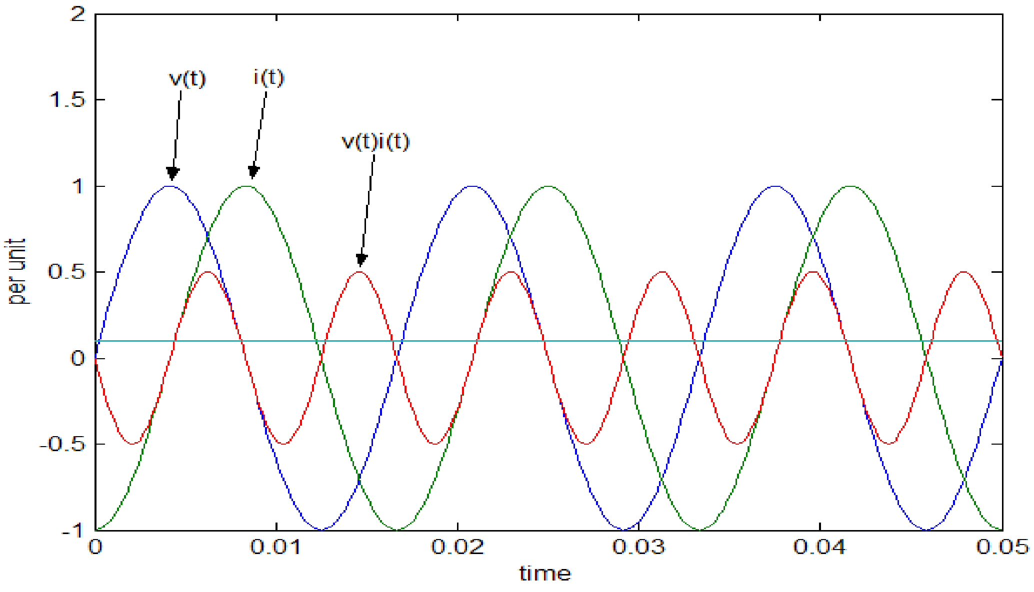
The Poynting vector

S **= [*E*] X [*H*]**

$$u \times v = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ u_r\, cos(u_\theta) & u_r\, sin(u_\theta) & u_z \\ v_r\, cos(v_\theta) & v_r\, sin(v_\theta) & v_z \end{vmatrix} = \begin{vmatrix} \hat{r} & \hat{\theta} & \hat{z} \\ u_r & u_\theta & u_z \\ v_r & v_\theta & v_z \end{vmatrix}$$



An application to the measurement of lost active power in a shunt reactor

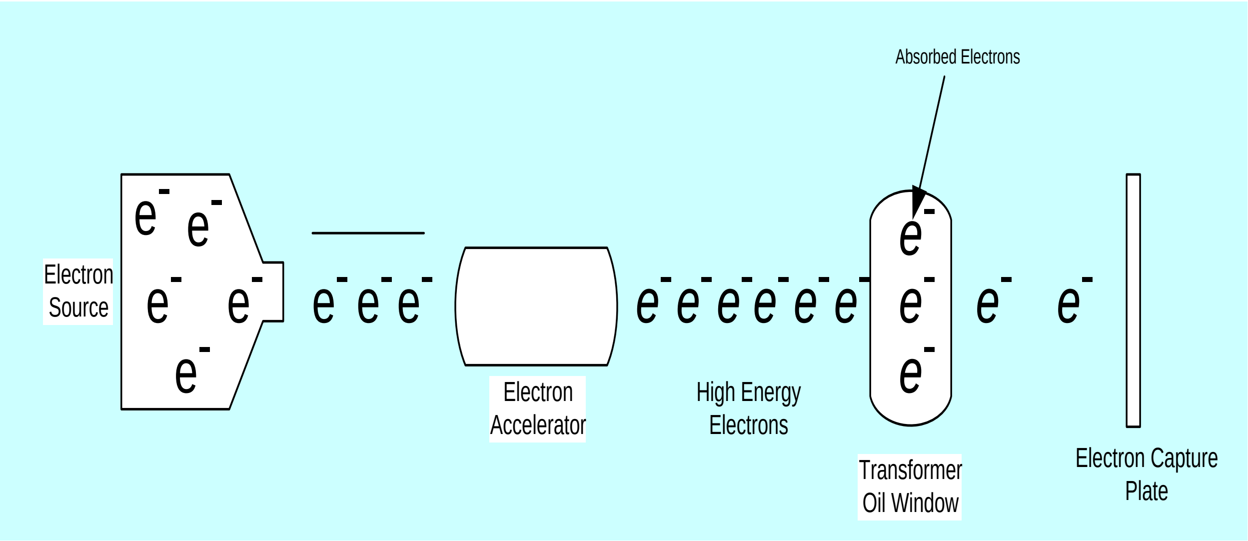


Voltage and current are nearly 90 degrees out of phase – the low power factor is not zero due to losses

Value of a Poynting vector sensor

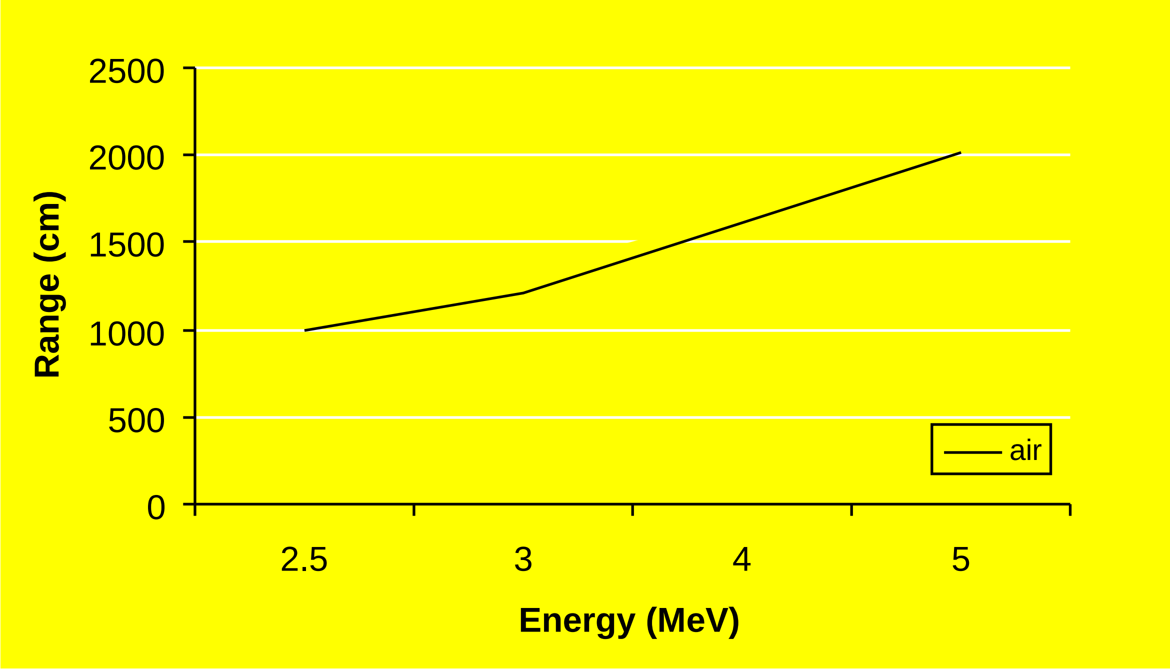
- Can be used to detect low level losses in systems with high levels of through power
- Can be used to detect low level losses in systems with very low power factor
- Can pinpoint location of losses – perhaps a discharge sensor

Alpha particle technology



Insulating oil integrity assessment using atomic particle absorption

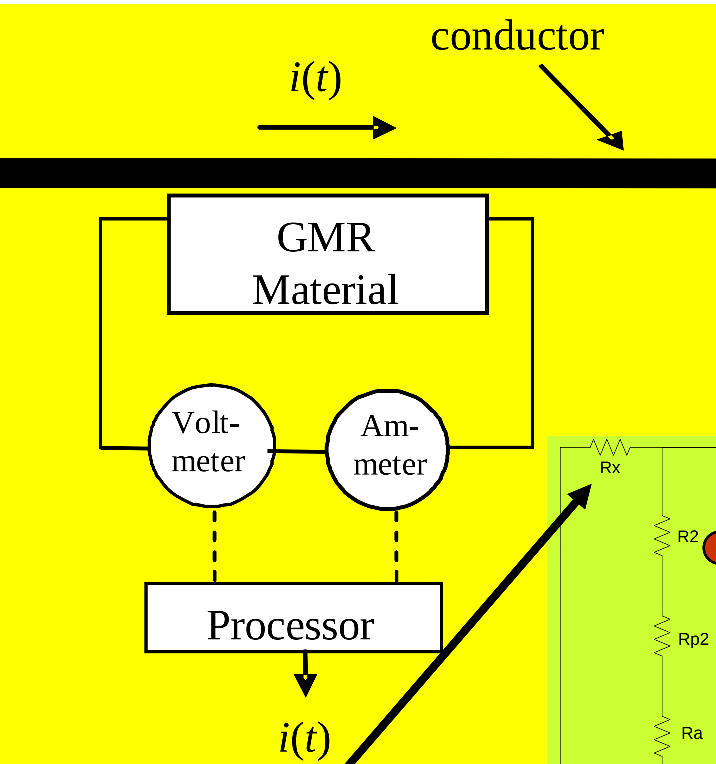
Absorption of alpha particles from an atomic source (as in a smoke alarm) can indicate the integrity of insulating oil



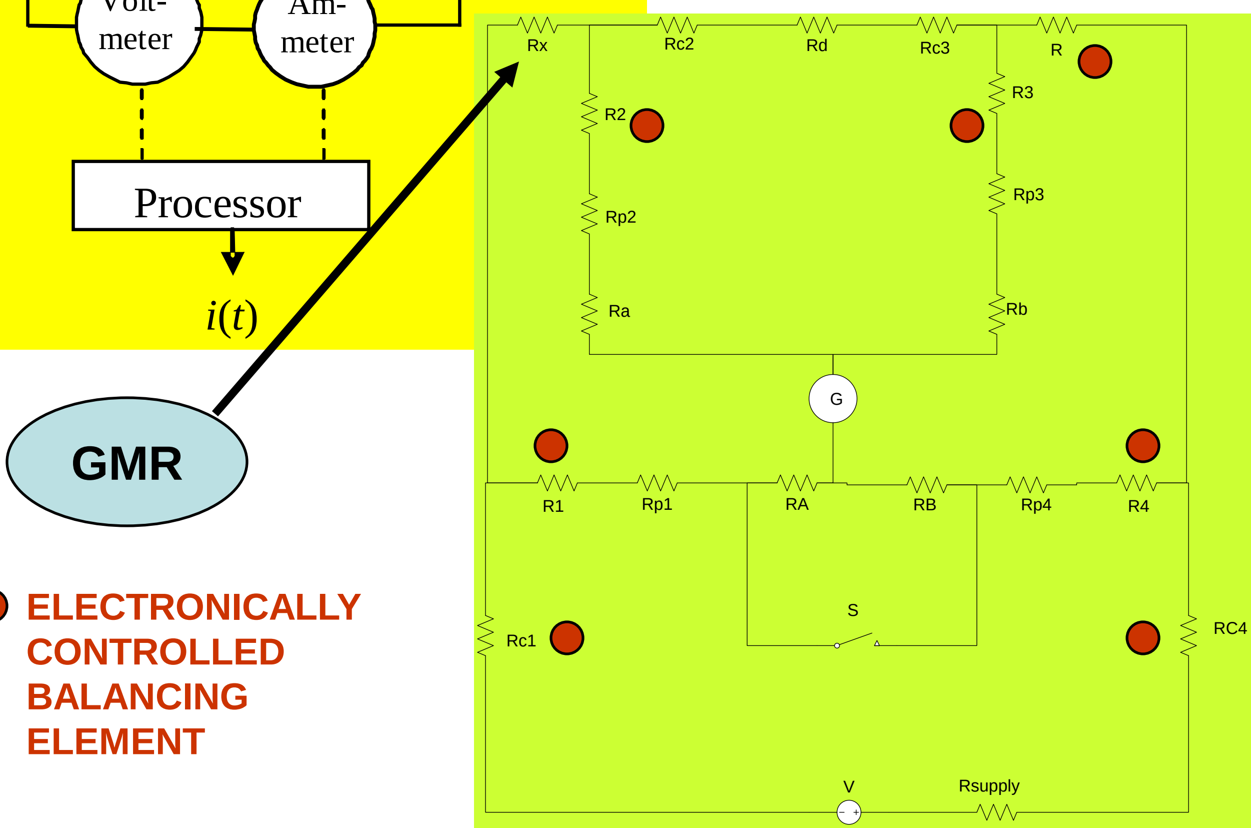
Potential applications of an alpha particle sensor

- **Insulating oil integrity tests**
- **Nondestructive testing of insulating oils**
- **Transformer oil signature analysis and detection – for incipient failures**

A giant magnetoresistive sensor (GMR)



The basic concept is a resistance measurement which is proportional to local magnetic field – and hence transmission line conductor current



● ELECTRONICALLY CONTROLLED BALANCING ELEMENT

Requires sensitive resistance measurement – e.g., via a Kelvin bridge

Double bridge balancing

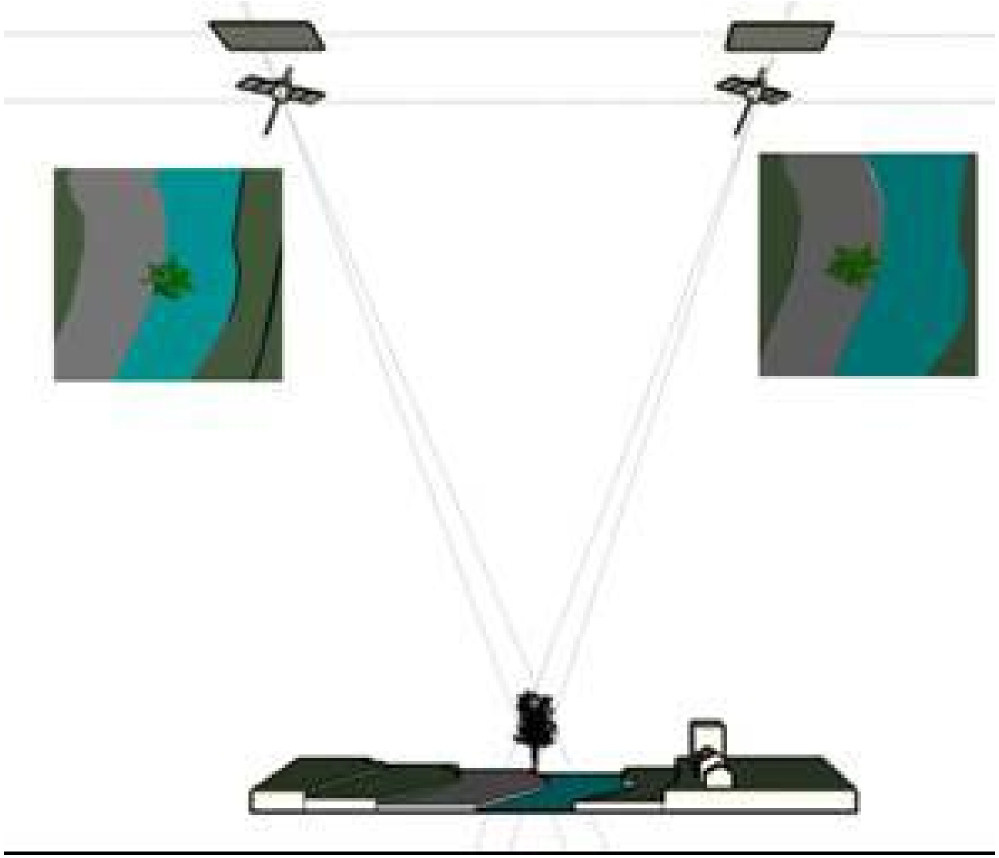
Wide bandwidth – basically limited by the speed of the electronic bridge balancing

Potential applications of GMR technology

- **Laboratory current measurements (even at high voltage)**
- **Local magnetic field measurements – e.g., a hand held *B* field instrument**
- **A wideband CT**

Satellite image technologies

- Tree trimming prioritization
- Physical security assessment



Stereo imaging

Satellite images

- **The accuracy of the identification of ground objects depend on the ground sample distance *GSD* value**
- **Satellite images are divided into pixels, *GSD* is the pixel diameter in meters**
- ***GSD* = 1 m needed for the tree height determination and *GSD* = 4 - 5 m are suitable for healthy vegetation identification**
- **Multispectral stereo images can be obtained from a satellite**
  - **IKONOS, *GSD* = 1 m, multispectral *GSD* = 4 m**
  - **QuickBird, *GSD* = 0.61 m**
  - **OrbView, *GSD* = 0.41 m, multispectral *GSD* = 1.64 m**

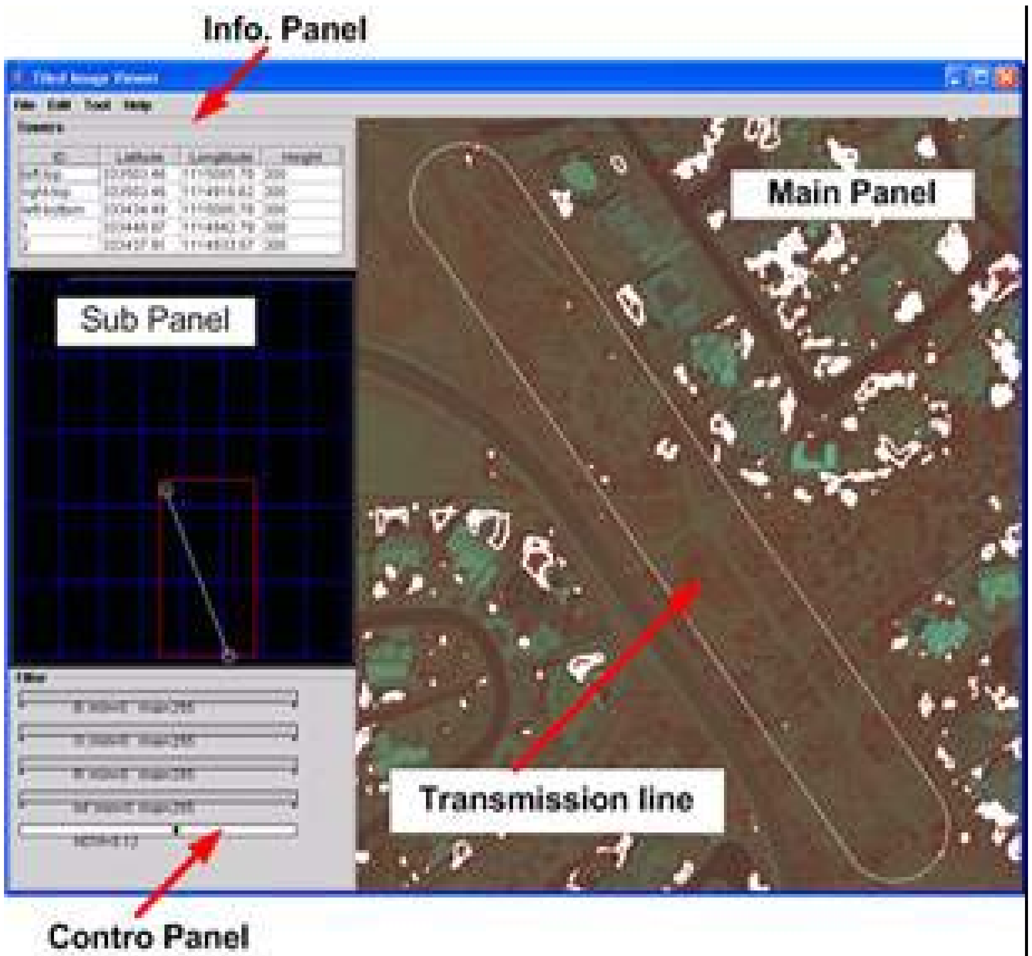
Software development for tree trimming prioritization using satellite images

The procedure is divided into ten steps:

1. Load a pair of multispectral stereo satellite images
2. Load the data of transmission line towers
3. Calculate the pixel location of the lines and towers on the image
4. Load the coordinates of the danger zone
5. Display the danger zone
6. Select the threshold value for detecting vegetation
7. Detect the healthy trees and plants within the danger zone
8. Calculate stereo matching for each pixel within the danger zone
9. Generate three dimensional Digital Surface Model
10. Identify high trees and plants within the danger zone endangering the line

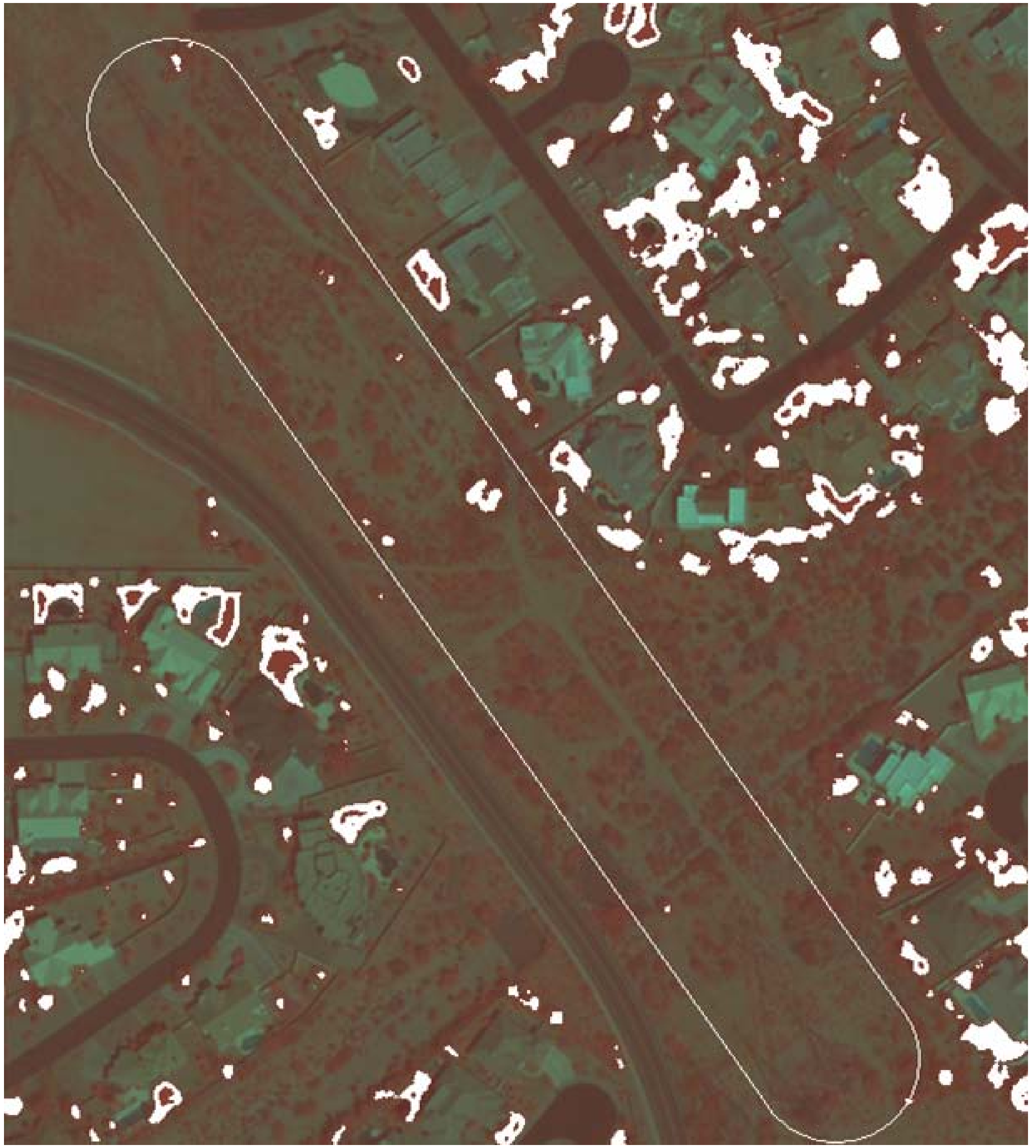
Software development: a GUI

The graphical user interface



- The main panel shows a satellite image and overlays results of analysis
- A sub-panel displays the transmission tower as a small circle and the transmission line as a line
- A control-panel gives index numbers which are used to interactively identify the land type such as bare land, trees, and buildings
- An info-panel displays a table of the list of geographical coordinates of transmission towers

Case study 1



- The figure illustrates the identification of areas with healthy vegetation

- QuickBird satellite image with a multispectral *GDS* = 0.61 m was used

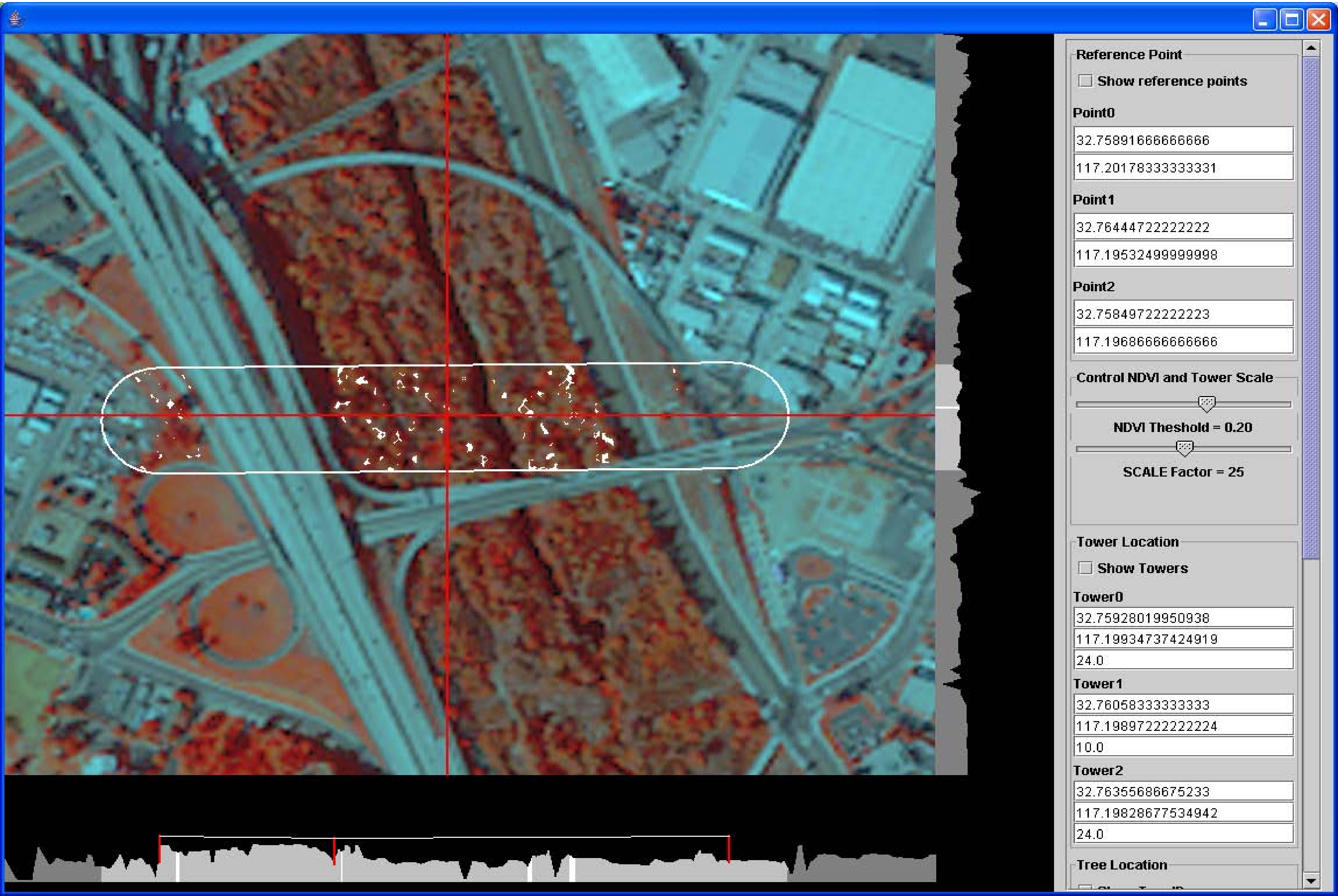
- Location: Scottsdale, Arizona

- White areas identify trees or healthy bushes from multichromatic analysis

Case Study 2

- **Location: San Diego, CA**
- **IKONOS satellite images, *GSD* = 1 m**
- **The transmission towers are located on the opposite sides of a freeway (I-8), and the overhead lines cross the freeway**
- **There is a vegetation area along the right of way – along the San Diego River (at Mission Bay Park)**
- **High trees are depicted in white, the white oval defines the study area**
- **A profile view appears at the bottom of the main panel**

Results: case study 2



Case study 2

During the scanning each pixel is analyzed by calculating the normalized differenced vegetation index (*NDVI*) defined as,

NDVI = (NIR – R) / (NIR + R)

***NIR* = near infrared, *R* = red.**
This minimizes the impact of variations in transmissivity from ground to satellite.

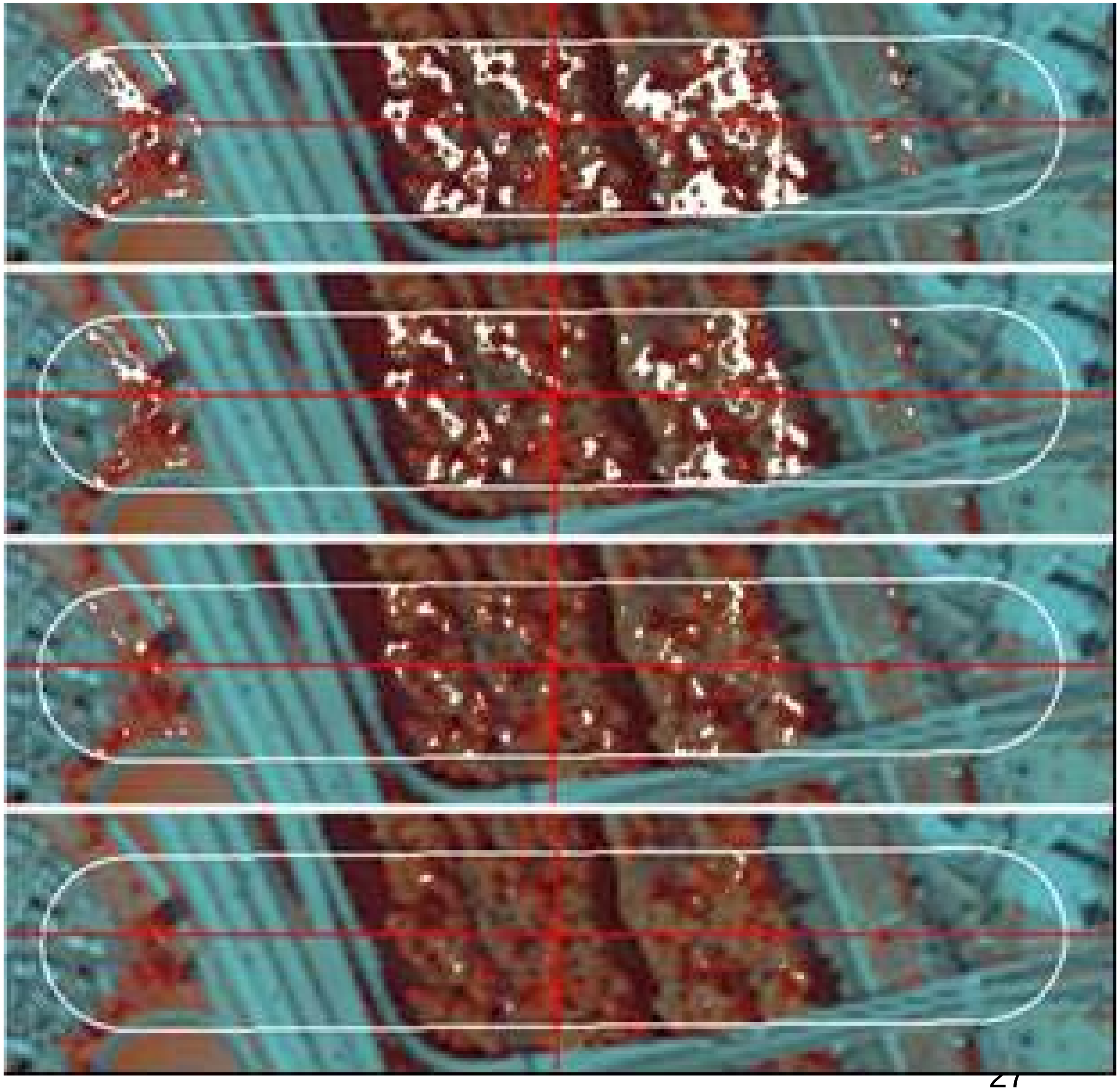
The effect of NDVI threshold on an IKONOS image illustrated here. The multispectral satellite image is, from top to bottom:

a) NDVI = 0.10

b) NDVI = 0.15

c) NDVI = 0.20

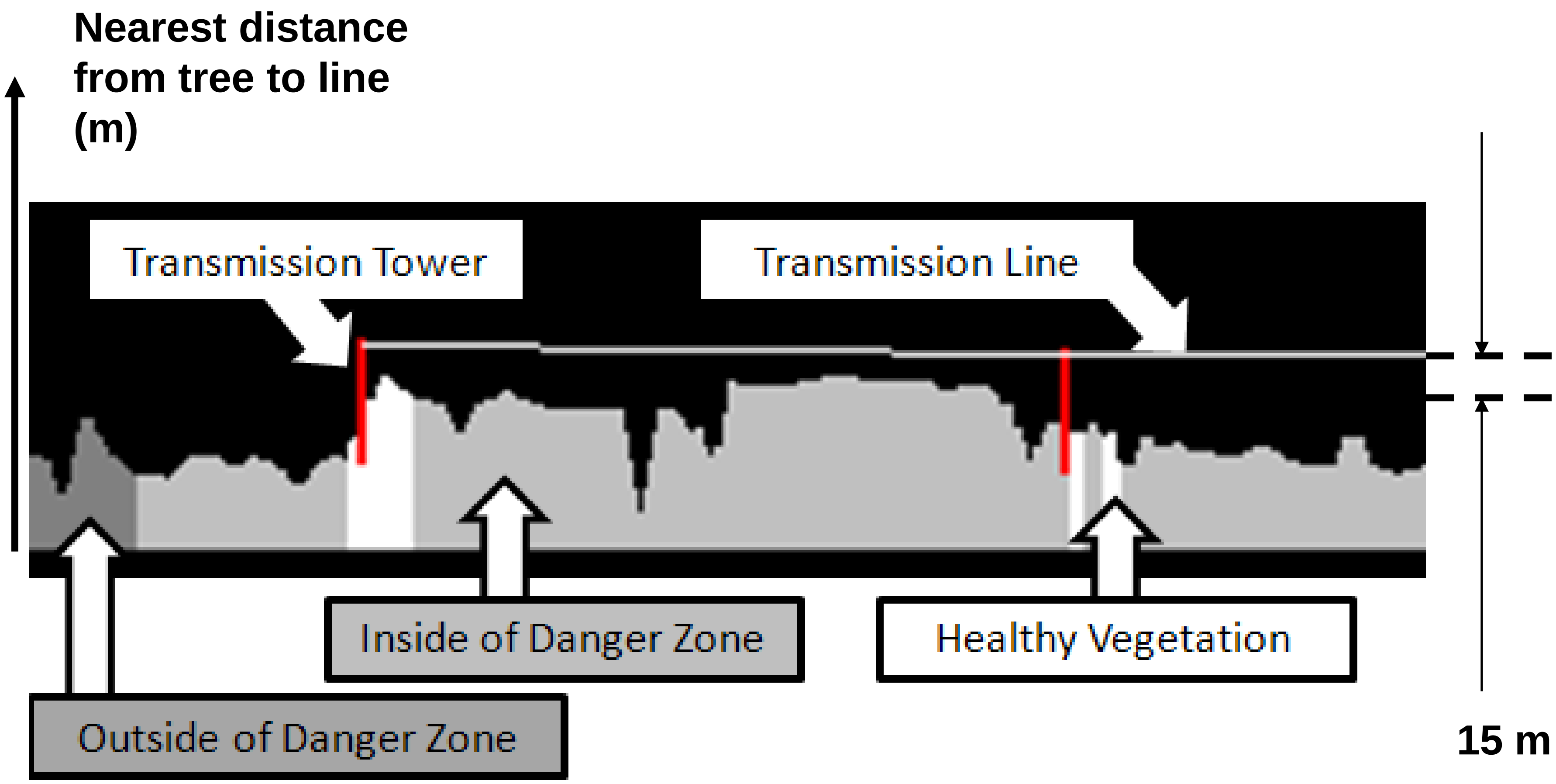
d) NDVI = 0.25



Case study 2

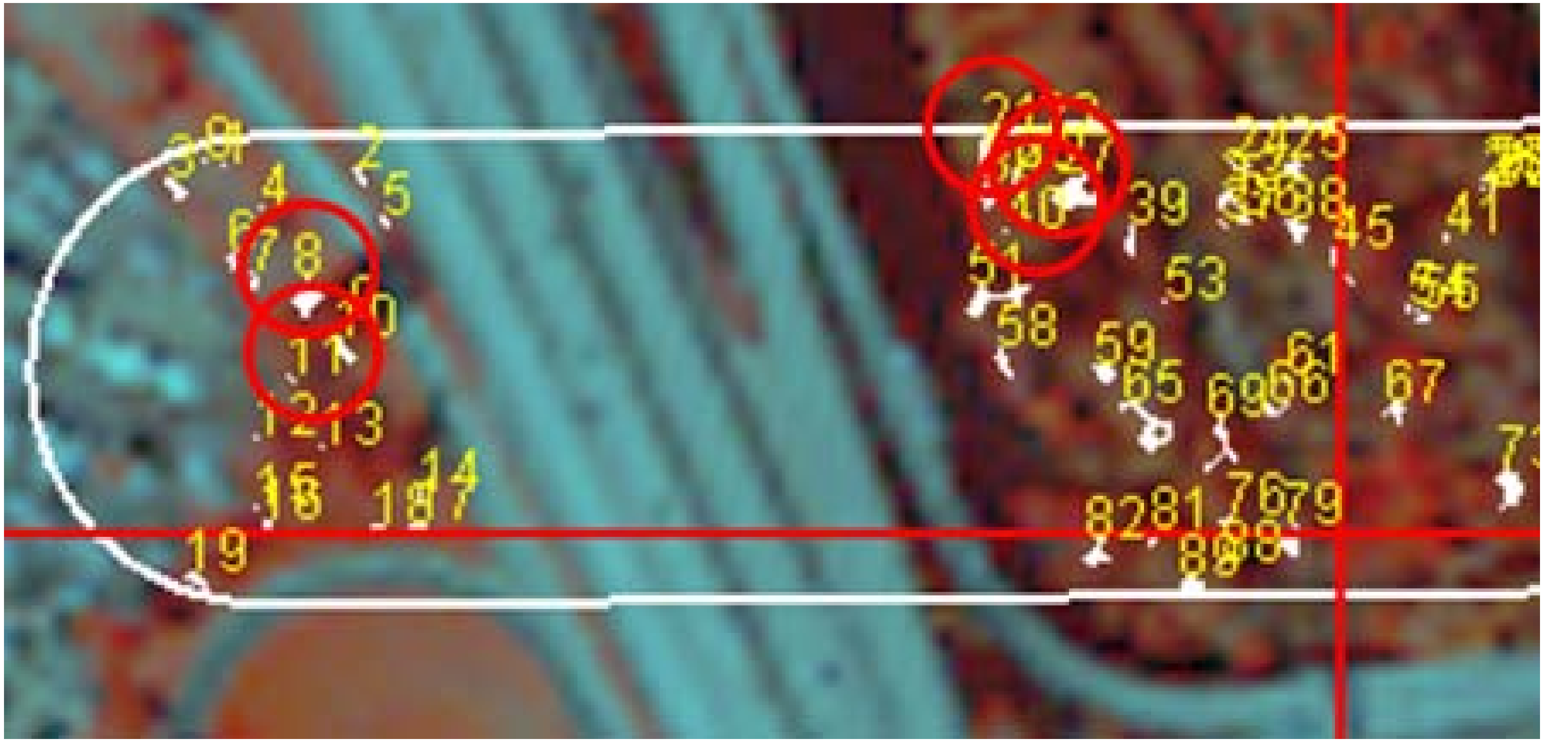
ID	Latitude (^oN)	Longitude (^oW)	Distance to lines (ft)
0	32.759251042034705	117.19985426770678	40.78245
1	32.75928400942072	117.1998345690552	42.64533
2	32.75953096171785	117.19973683669522	32.101067
3	32.75918758139942	117.19980425768894	38.711155
4	32.759336868606894	117.1997209176232	42.473488
5	32.759566403240605	117.19962773072264	31.185623
6	32.75927090915831	117.19960498847946	47.045143
7	32.75929827272182	117.19955346662981	48.571705
8	32.759388466048144	117.1994966434048	26.227222
9	32.759457505829374	117.19942315017384	32.37095
10	32.75943572141182	117.19935116877471	32.37095
11	32.75932871661798	117.19931252240548	24.45303
12	32.75923663067426	117.19920341145091	54.78344

Case study 2


Nearest distance from tree to line (m)
Transmission Tower
Transmission Line
Inside of Danger Zone
Healthy Vegetation
Outside of Danger Zone
15 m

Case study 2

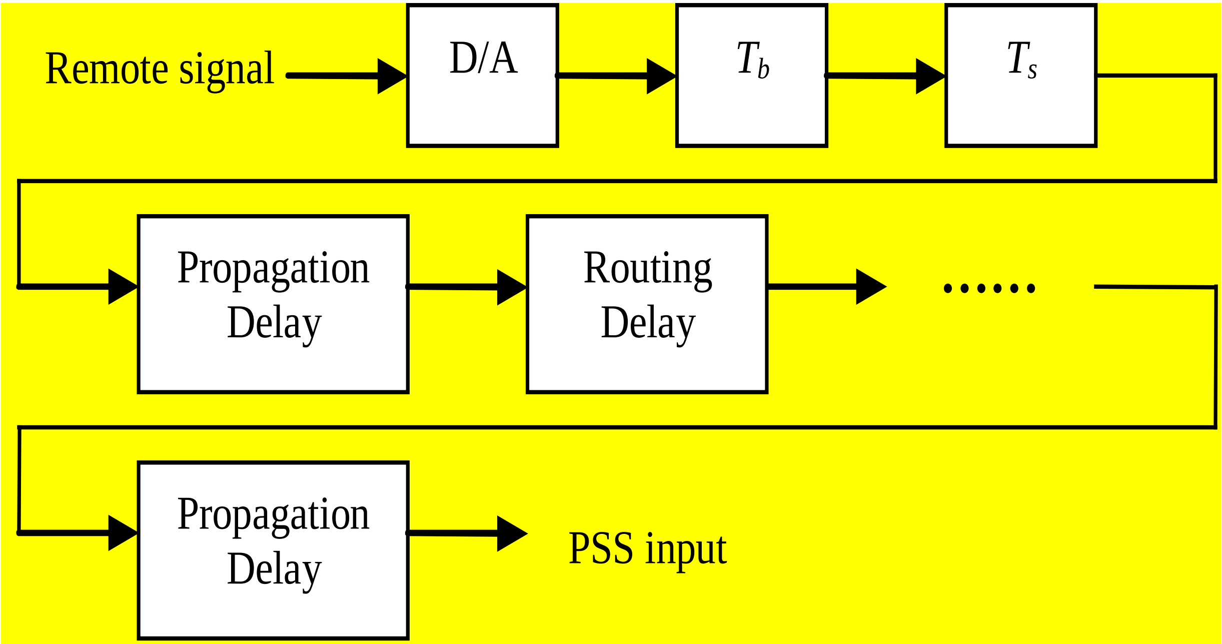
The five closest trees to transmission lines are extracted from the tree list and these are marked



Contemplated risk and cost to benefit ratio of new sensors

Need	Estimated risk	Estimated cost / benefit ratio
Very low cost sensors*	Moderate	Very favorable
Direct measurement sensors	Moderate	Very favorable
Increase dynamic range of PTs and CTs	Low - moderate	Favorable
Development of semiconductor sensors	Moderate	Very favorable
Techniques using 'non-sensors'	Low	Very favorable
Digital signal processing development for sensors	Low	Very favorable
Measurement of conductor sag	Low	Very favorable
Piezoelectric sensors	Moderate	Unknown
Very low current measurement	Low	Unknown
Transformer loss and temperature measurement	Low	Favorable
Video applications	Low	Favorable
Audio sensors	Low	Favorable
Double (Kelvin) bridge and other innovative bridge circuits	Low	Unknown

Latency – wide area measurement and control systems



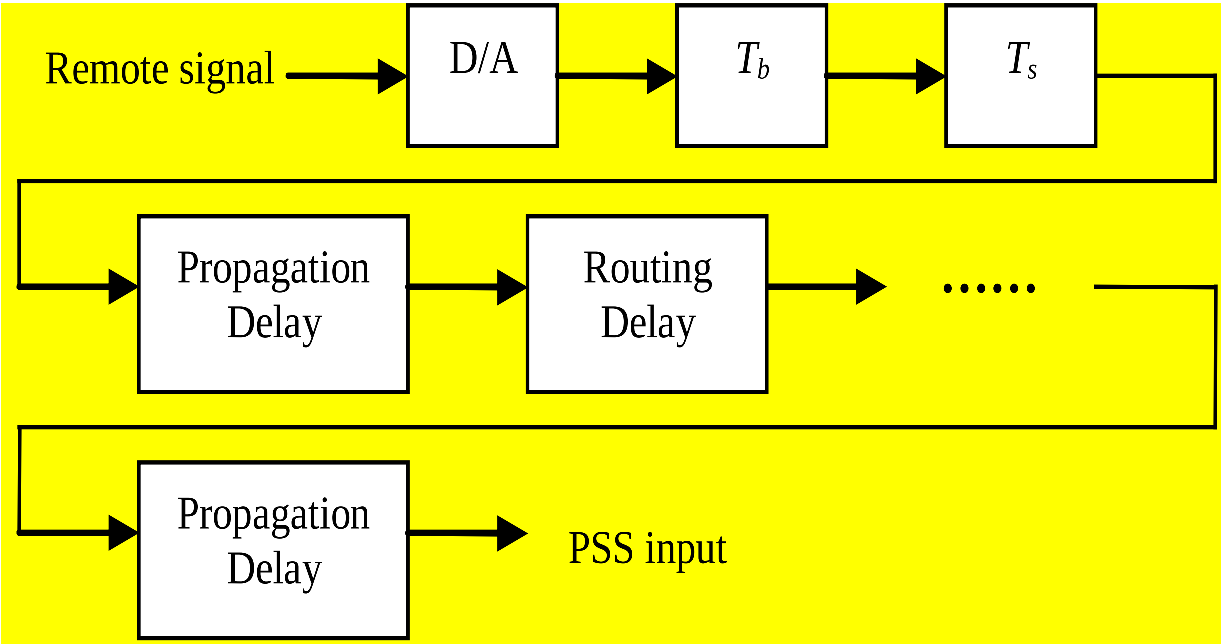
Latency
in delivering sensory signals

$$T = T_s + T_b + T_p + T_r$$

$$T_s = \frac{P_s}{D_r}$$

$$T_p = \frac{\ell}{v}$$

T_s is the serial delay, T_b is the between packet delay, T_p is the propagation delay, T_r is the routing delay, P_s is the size of the packet (bits/packet), D_r is the data rate of the network, ℓ is the length of the communication medium, and v is the velocity at which the data are sent though the communications medium (e.g., 0.6c to c, where c is the speed of light).



Latency

in delivering sensory signals

$$E(T)=\begin{bmatrix}\frac{-P_s}{D_{ro}^2} & 1 & 1\end{bmatrix} E\begin{pmatrix}D_r\\ T_p\\ T_r\end{pmatrix}+T_b+\frac{2P_s}{D_{ro}}$$

It is possible to estimate the mean and variance of the latency

$$\sigma_T^2=\begin{bmatrix}\frac{-P_s}{D_{ro}^2} & 1 & 1\end{bmatrix}\begin{bmatrix}\sigma_{DrDr}^2 & \sigma_{DrTp}^2 & \sigma_{DrTr}^2\\ \sigma_{TpDr}^2 & \sigma_{TpTp}^2 & \sigma_{TpTr}^2\\ \sigma_{TrDr}^2 & \sigma_{TrTp}^2 & \sigma_{TrTr}^2\end{bmatrix}\begin{bmatrix}\frac{-P_s}{D_{ro}^2}\\ 1\\ 1\end{bmatrix}$$

Calculation tools: the stochastic case

$$E(T) = \begin{bmatrix} \frac{1}{D_r} & 1 \end{bmatrix} \begin{bmatrix} E(P_s) \\ E(T_r) \end{bmatrix} + T_b + T_p$$

$$E((T - E(T))^2) = \begin{bmatrix} \frac{1}{D_r} & 1 \end{bmatrix} \begin{bmatrix} \sigma^2_{PsPs} & \sigma^2_{PsTr} \\ \sigma^2_{TrPs} & \sigma^2_{TrTr} \end{bmatrix} \begin{bmatrix} \frac{1}{D_r} \\ 1 \end{bmatrix} = \sigma^2_T$$

- **These formulas are distribution free – they do not depend on type of stochastic variation**
- **Allows the estimate of the mean latency, and the variance (square of the SD)**

The WECC example

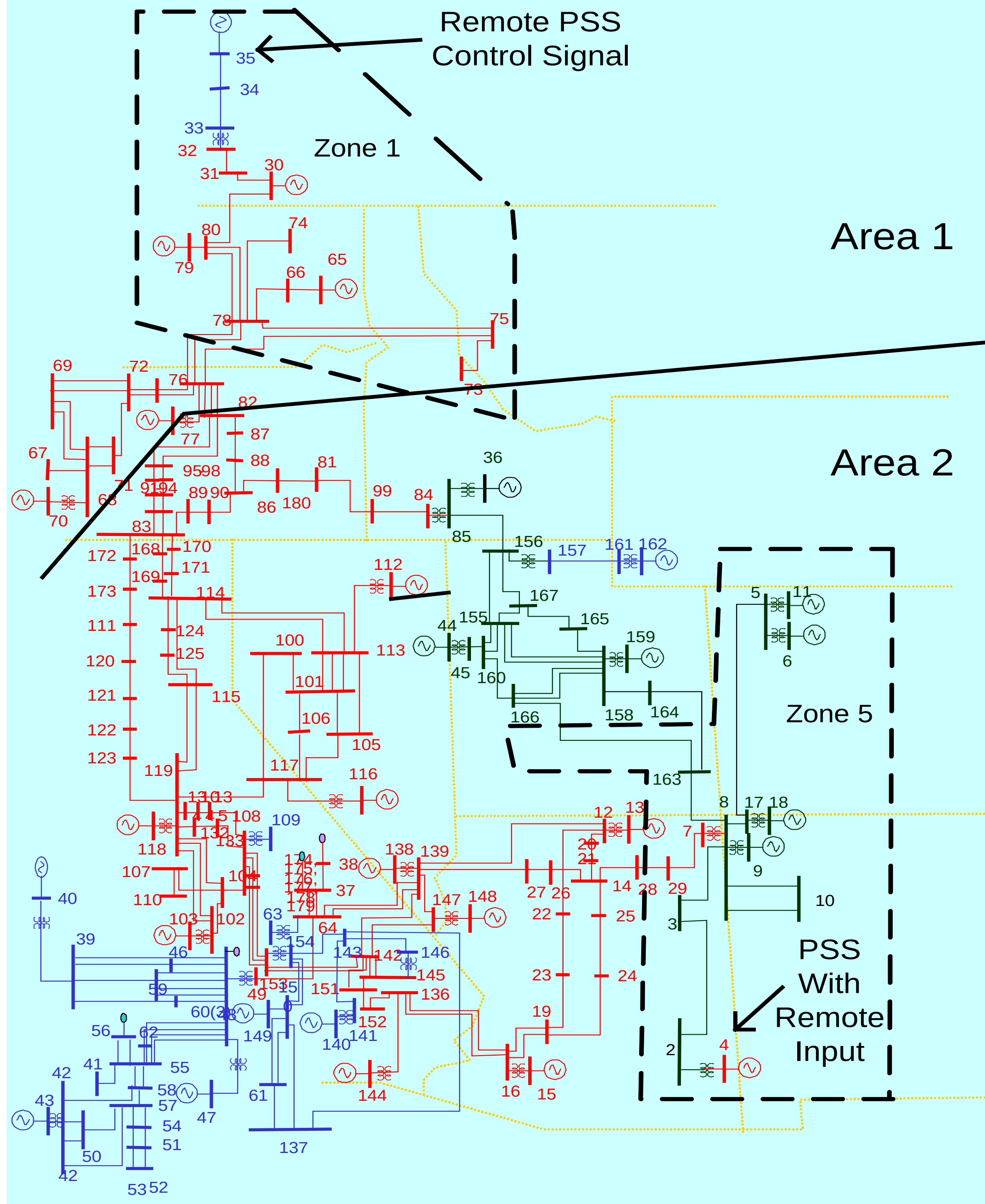
The WECC system has nearly 30,000 buses above 69 kV. It is assumed that nearly one-fifth to one-quarter of these buses are, in fact, instrumented and ultimately result in measurements. For purposes of obtaining an illustrative example, the communication infrastructure of a WACS for the WECC is postulated.

The communications system specifications used in the WECC example are shown on the next slide. The table on the next slide shows the number of measurements for each zone and the maximum and minimum delay times for each of those zones (for a measurement in each of those zones to a central location ℓ km away).

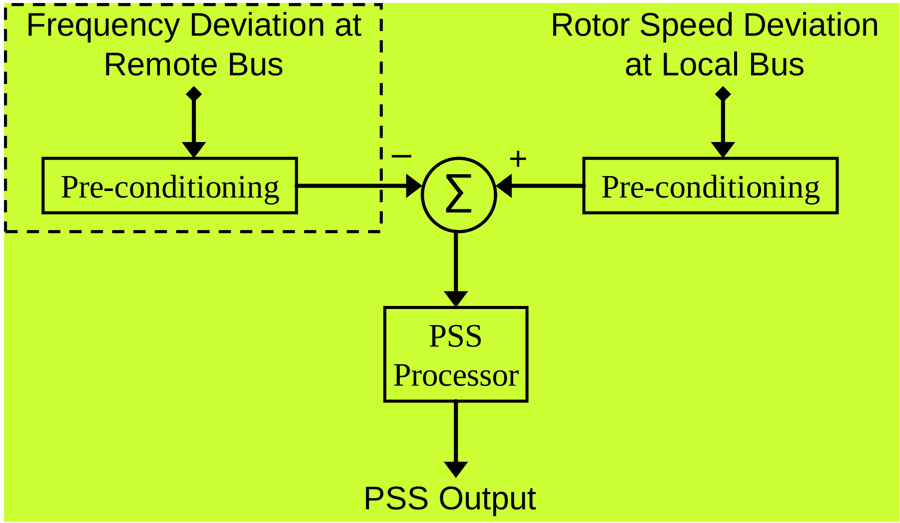
Data rate of the network	D_r	**50 *Mbps***
Between packet delay	T_b	**0**
Packet size	P_s	**200 *b***
Length of the communication medium	ℓ	**1000 *km***
Data velocity	V	**0.6*c***
Measurement rate	Λ	**50 (packets/s)**
Router serving rate	**M**	**50 *Mbps***

Calculated delay times

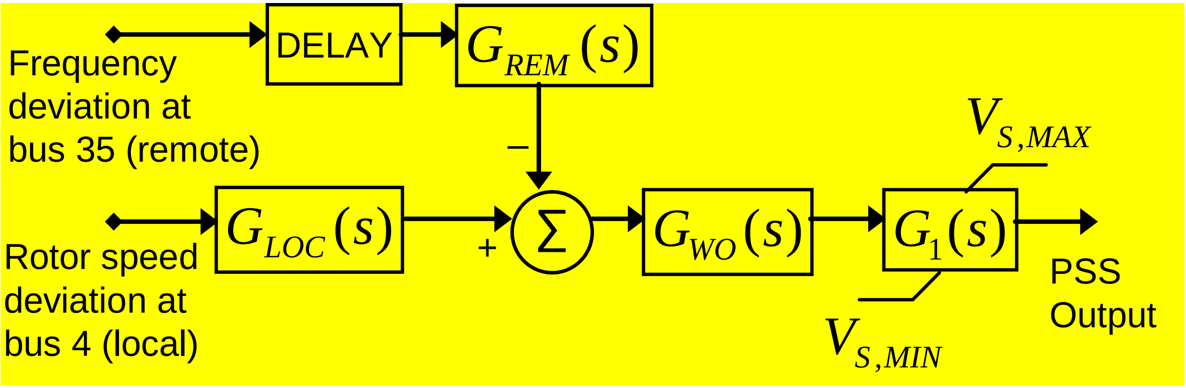
	Number of measurements	Minimum delay time (*s*)	Maximum delay time (*s*)
Zone 1	470	0.0206	0.0220
Zone 2	907	0.0206	0.0222
Zone 3	1310	0.0208	0.0222
Zone 4	840	0.0207	0.0222
Zone 5	504	0.0207	0.0220
Zone 6	638	0.0207	0.0222
Zone 7	1176	0.0219	0.0222
Zone 8	1008	0.0207	0.0220



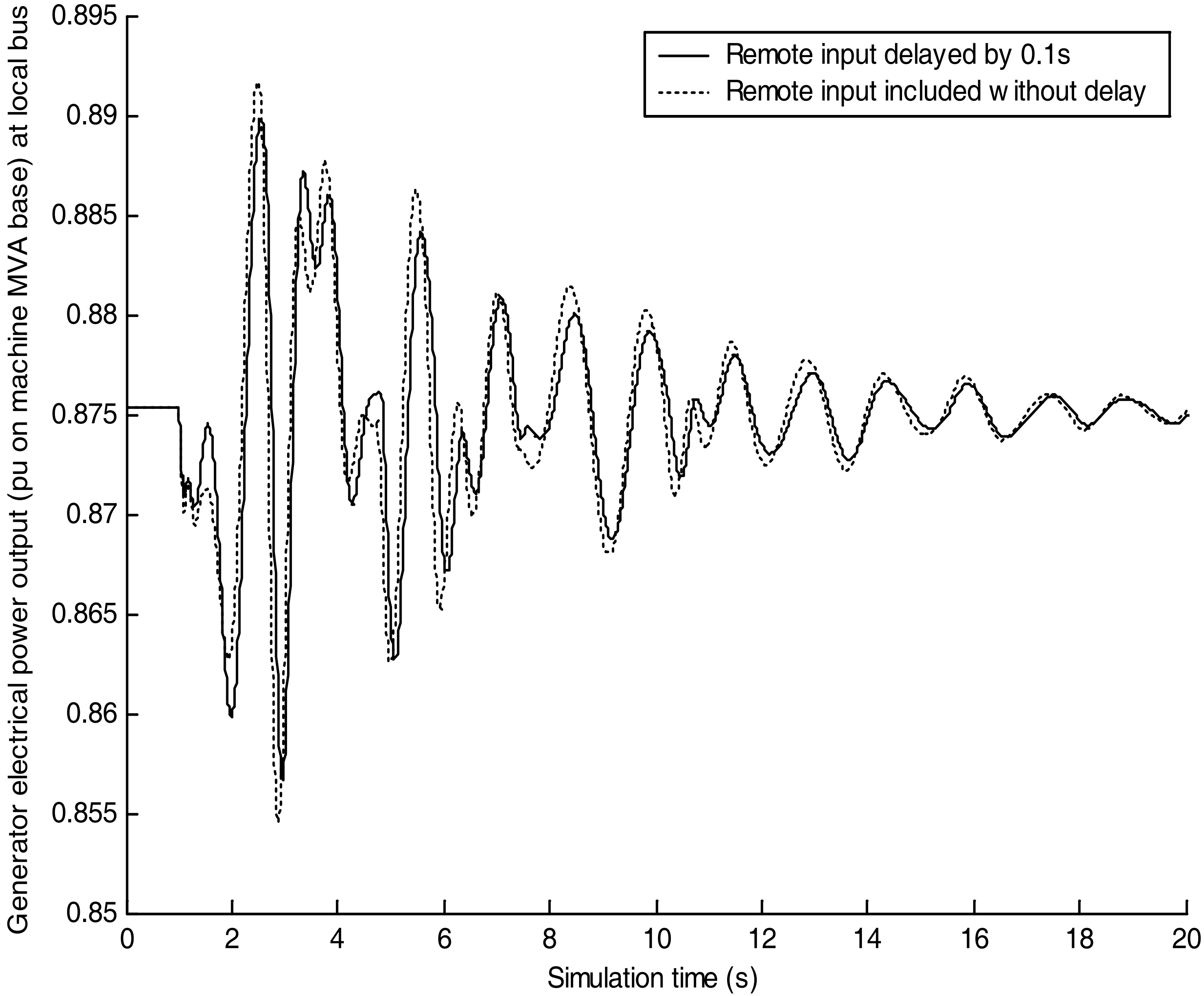
Implications of latency – WECC example



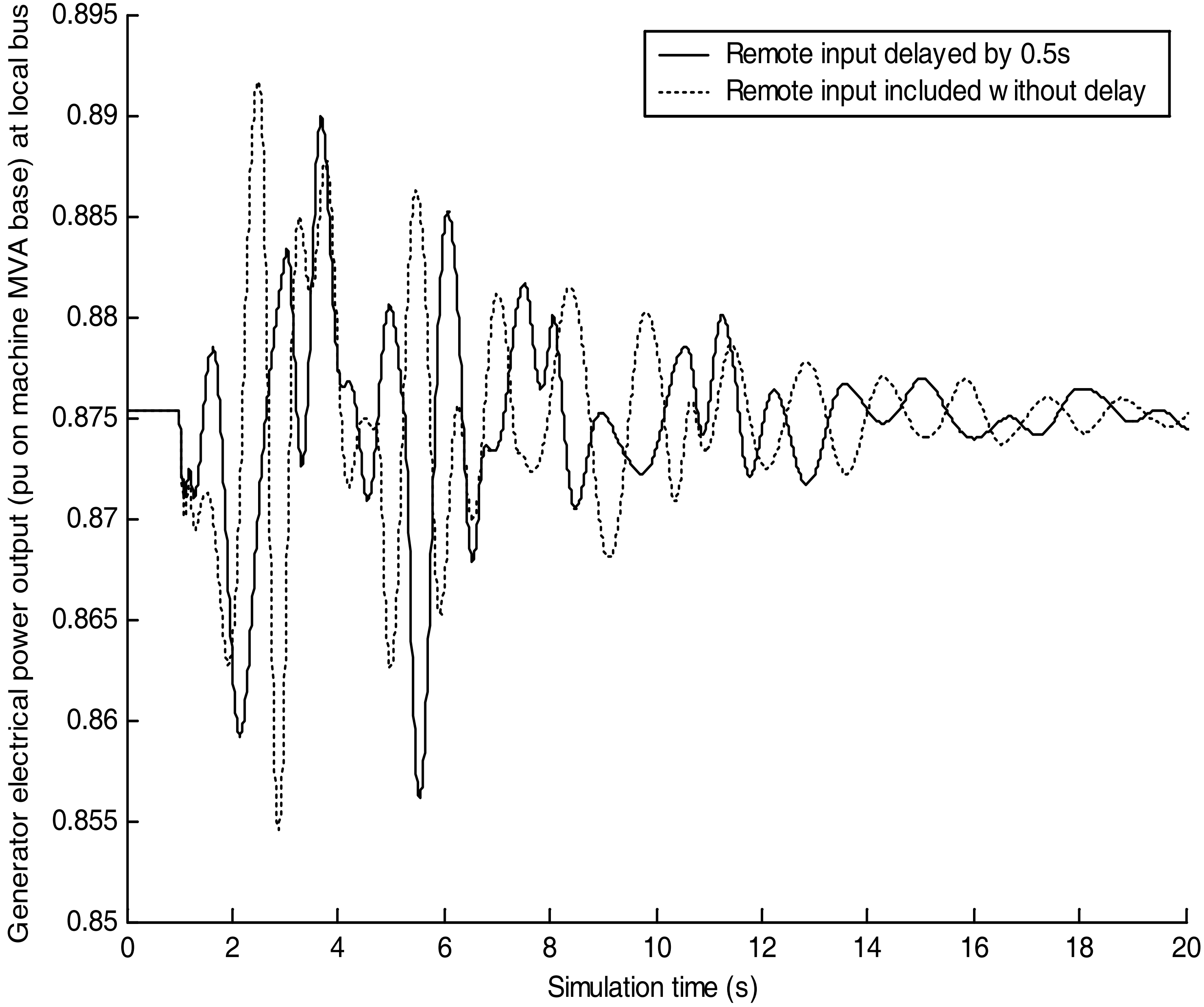
Purpose	*Value*
Gain for local input	**5**
Communication latency	**Variable**
Low-pass filter (lag)	**20/(1+s)**
Washout	**10/(1+10s)**
Phase compensation	$\frac{1+0.3s}{1+0.03s}\cdot\frac{1+0.3s}{1+0.03s}$
Lower output limit	**-0.1 p.u.**
Upper output limit	**+0.1 p.u.**



In order to assess the impact of latency, the same WECC example is reconsidered with PSS measurements and controls implemented.



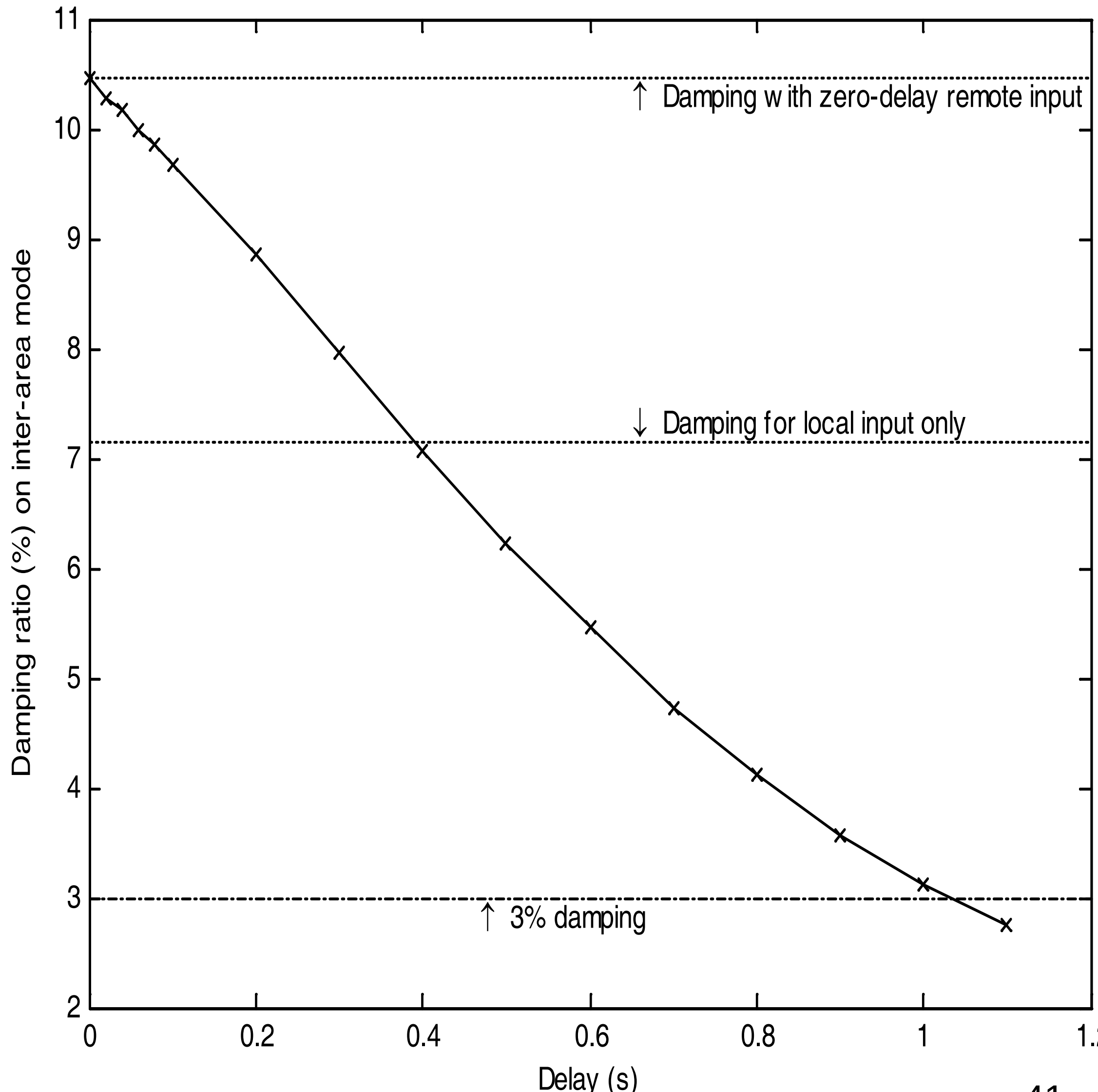
Impact of 0.1 s delay



Impact of 0.5 s delay

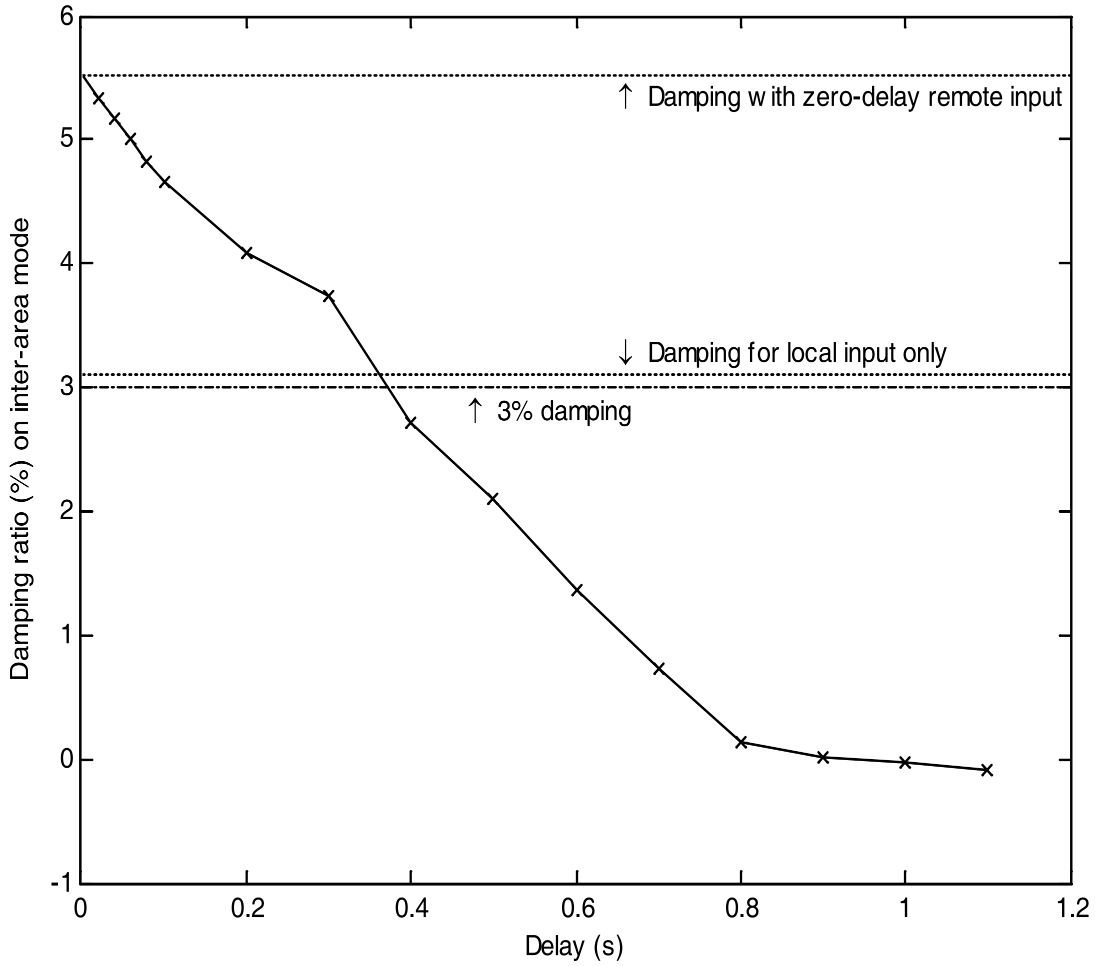
Impact of latency

- **Latency increases settling time** (graph at the right is the impact of delaying the remote bus frequency input from bus 35 to the PSS at bus 4 on interarea damping)
- **There are cases in which latency in PSS signals result in instability**
- **Long latency times (e.g., > 0.25 s) show the greatest number of problematic cases**



Impact of latency

- **The latency issue is worse for cases of transmission circuit outages**
- **For example: the impact of delaying the remote bus frequency input from bus 35 to the PSS at bus 4 on interarea damping with a double circuit outage**



Main conclusions from the latency study

- A straightforward calculation method and model of communication delays in power system WACS are shown for the case of dedicated sensory communication channels.
- Utilizing data representative of the WECC system, for a 50 Mbps network, an approximate interarea time delay of 20.6 ms is found.
- The standard deviation of the total interarea delay time may be calculated as well – and a typical value is about 4.6 ms.
- The latency calculations have been applied to a WACS test case. Introducing a remote input to a single PSS has been shown to enhance the stability of the test case by increasing the damping of the interarea mode under study. Latency has the effect of reducing the effectiveness of controls. However, WACS, with its attendant latency, appears to be more effective than local control in damping interarea oscillations.
- If additional processing delays were to exist, especially of the order of those introduced by satellite based communication, or data routing delays, conditions of underdamping (e.g., below those allowed operationally) will need to be checked carefully.

Some concluding remarks on the massive use of sensors in power systems

Advantages of deployment of sensors

1. **Advanced warning of developing problems resulting in a fewer catastrophic failures.**
2. **More efficient operations of equipment and overall system resulting in lower losses, better conservation of resources and optimum operation.**
3. **Improved emergency response to problems; operators will have more information to diagnose and deal with problems for both normal and emergency operations.**
4. **Increased security of power grid, thereby, enhancing the homeland security.**
5. **Improved redundancy results in improved reliability of the measurements.**

Examples of innovative sensory technology

- Poynting vector (an electromagnetic combination of electric and magnetic field) instrumentation may offer the capability of measurement of low electric and magnetic fields. The main issues to be addressed are the shielding of the sensor to reveal specific components of the Poynting vector. The instrumentation of the Poynting vector for electric power applications is a high risk venture.
- Measurement of atomic particle absorption (e.g., for detection of transformer oil contamination)
- Utilization of satellite electromagnetic (e.g. GPS) methods for sag identification of overhead transmission circuits, processing of satellite images for tree trimming prioritization
- Use of time stamped remote measurements for PSS signals

Questions – Comments – Remarks