Real-Time Avalanche and Landslide Analysis through Sensor Networks with High Speed Local Positioning

Edoardo Charbon
Processor Architecture Lab (LAP)

Christophe Ancey
Environmental Hydraulics Lab (LHE)

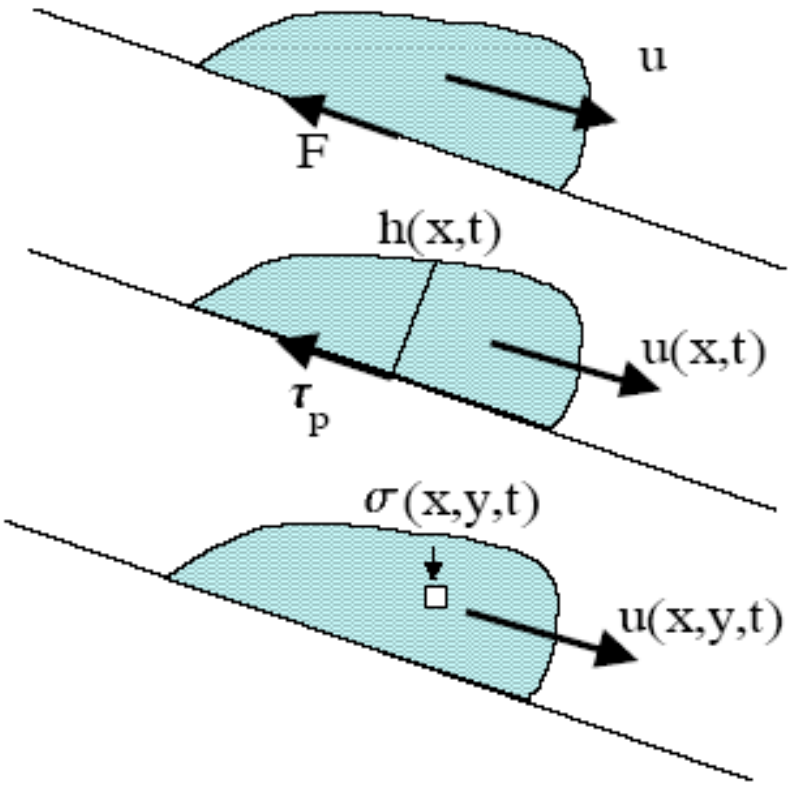
LABORATOIRE HYDRAULIQUE ENVIRONNEMENTALE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Goal

- **What we want to do**
  - **Analyze the dynamics of a an avalanche or a landsliding mass in real time**
- **Where**
  - **In a controlled environment**
  - **In the field**
- **Why**
  - **To gain insight into currently unknown phenomena (scientific)**
  - **To model and validate novel sensor network paradigms (scientific)**
  - **To gain experience in distributed warning and monitoring systems for life saving purposes (social)**

Analytical Modeling



1-dimensional: Sliding block model

$$\frac{d^2\zeta}{dt^2} = g\sin\theta(\zeta) - \frac{F_t}{m}.$$

2D: « shallow-water » (flow-depth averaged) model

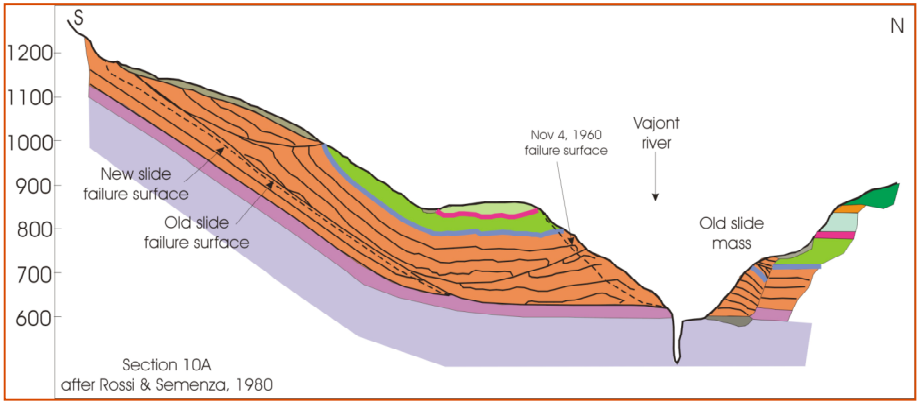
$$\frac{\partial h}{\partial t} + \frac{\partial h\overline{u}}{\partial x} = 0,$$

$$\bar{\varrho}\left(\frac{\partial h\overline{u}}{\partial t} + \frac{\partial h\overline{u^2}}{\partial x}\right) = \bar{\varrho}gh\sin\theta - \frac{\partial h\bar{p}}{\partial x} + \frac{\partial h\bar{\sigma}_{xx}}{\partial x} - \tau$$

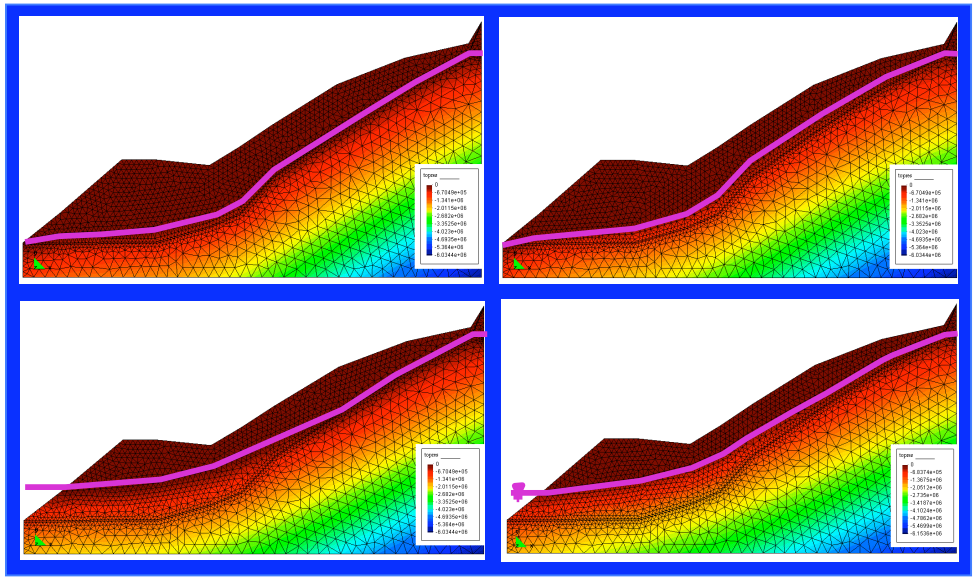
3D: none

[Ancey 04], [Ancey 109]

Numerical Modeling



Slope conditions



Bulk weight: 25 kN/m3

Rock friction angle: 23°-40°

Cohesion: 1Pa – 1 MPa

Young Modulus: 100 MPa

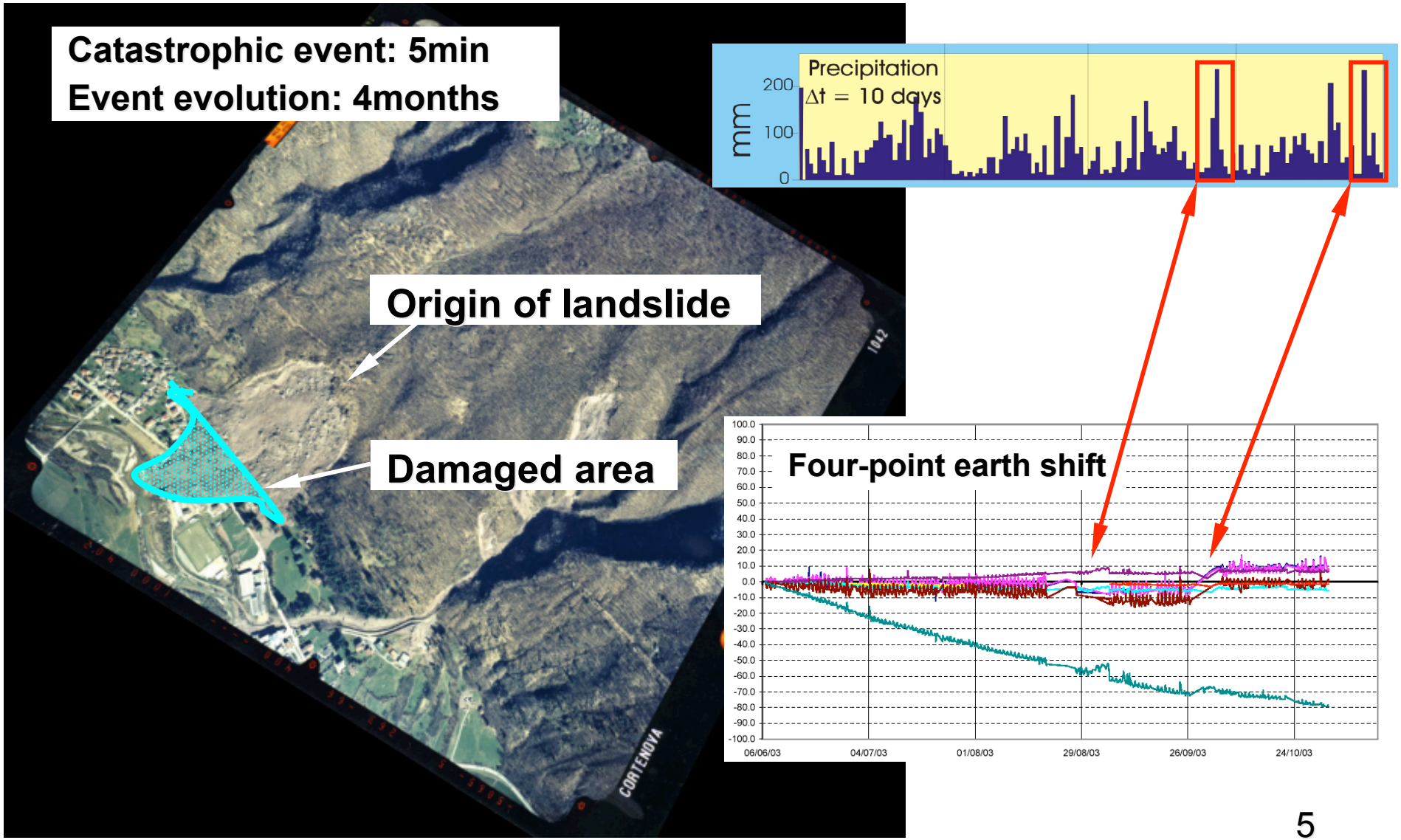
Pore pressure: Reservoir and groundwater

Failure surface friction angle : 8.74°

Cohesion: 0.15 Pa

Reduction factor for FS: 0.38

Warning Systems

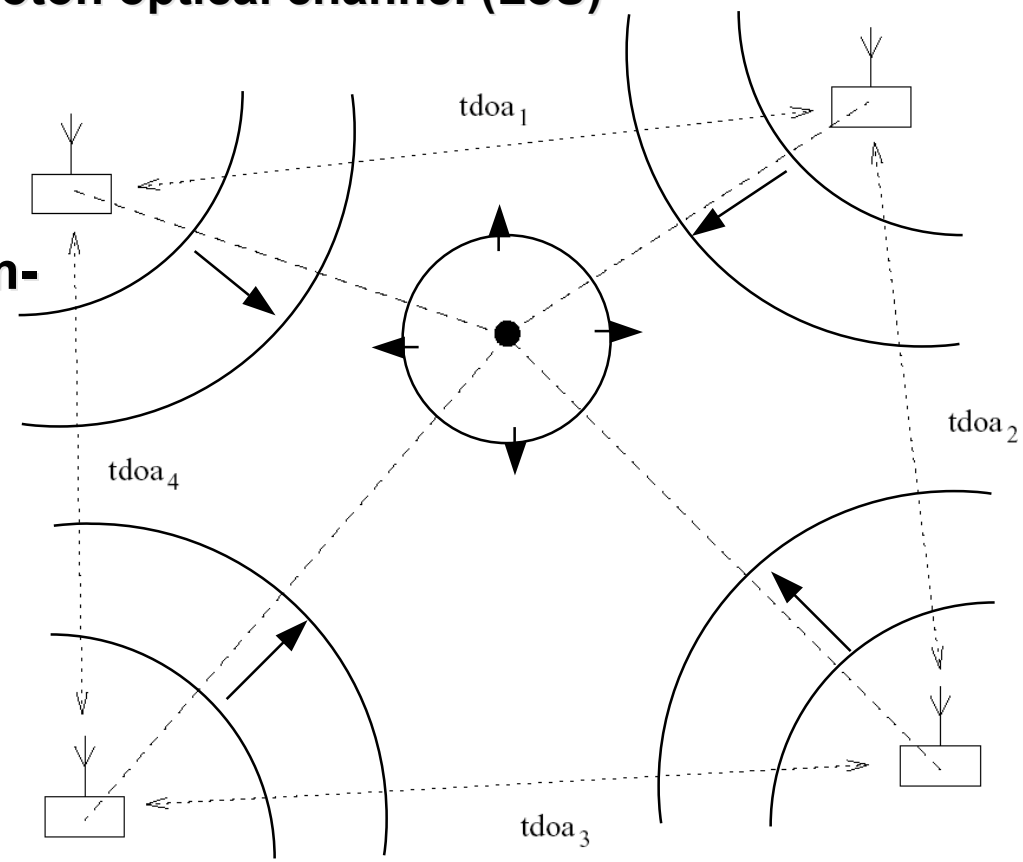


Motivation for Using Sensor Networks

- **Upon appropriate design, SN nodes can take strategic positions within avalanche/landslide front, body, and tail and *move with it***
- **With high speed, precise positioning, nodes can rely physical quantities to verify and improve theoretical models**
- **Through self-organized nature of SN, deployment and measurement is seamless**
- **Nodes can be deployed for months, thus enabling to monitor precipitation and other parameters**
- **Long-term deployment enables warning systems**

Proposed Approach

- Self-organized SN of reinforced nodes with OD antennas
- Local positioning system (LPS)
  - Reverse-GPS TOA on medium bandwidth RF system (less accuracy)
  - Direct-GPS TOA on single photon optical channel (LoS)
  - ps accurate time discrimination
- Transponder-like position update in nodes using RF com-link



Technical Challenges and Solutions

- Optical TOA
  - 30ps precision time discrimination at the node
  - Multireflection
  - Fading, range
  - → Approach: Single Photon Avalanche Detectors (SPAD) rangefinding [Charbon JSSC 05]
- RF TOA
  - Arrival of frequency pulse in presence of multipath
  - → Approach: mix of classical detection and Finite Rate of Innovation (FRI) based rangefinding [Vetterli 05]
- Time discrimination
  - 30ps accuracy time differential
  - → Approach: Time-to-digital Converter (TDC) rangefinding [Charbon ISSCC 05]

Expected Outcome & Scientific Contribution

- **Through off-board optical/RF LPS, a real-time high-precision positioning estimation will be possible in a self-organized SN**

Specification	Min.	Typ.	Max.	Unit
Resolution	-	3	10	cm
Accuracy	-	3	10	cm
Update Rate	1	10	33	s^{-1}
Range	250	500	1000	m
Number of nodes				-
Speed	1	10	20	m/s
Acceleration		9.81		m/s^2

- **For the first time, a number of FRI theoretical results will be tested on a self-organized SN, evolutionary FRI will be tested**
- **For the first time, inner-dynamics in avalanches and landslides will be studied in detail**
- **Potential impact in landslide/avalanche and warning systems**

Envisioned Cooperations

University/Lab	Projects	Contact Person
IC/LCAV	FRI theory and instruments	Dr. L. Sbaiz
ENAC/INTER/TOPO	Indoor navigation, localization for isolated workers, and general navigation algorithms	Prof. B. Merminod
Università degli Studi di Milano Bicocca	Landslide Dynamics Modeling	Prof. G. Crosta
Norwegian Geotechnical Institute	Slope stability, Slide Dynamics	Dr. P. Gauer
Technische Universiteit Delft	Natural Disaster Hazard and Risk Analysis	Prof. J. K. Vrijling
WSL	Rockfalling Dynamics Modeling	B.W. McArdell
University of Ljubljana	Flood Analysis and Warning	Prof. M. Brilly

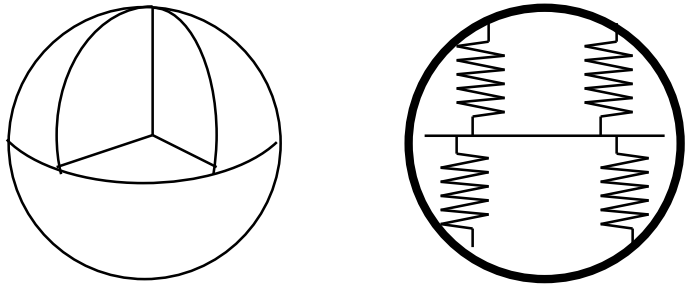
BACKUP

State-of-the-art in Positioning Systems

Technology/ Technique	System	Range [m]	Resolution [m]
TOA	GPS (worldwide)	>1000	0.1~10
IEEE 802.11 / TOA	TI	<30	0.5~1
IEEE 802.11 / RSS	"RADAR" (Microsoft)	<100	~5
915MHz / RSS	TinyOS LPS (UCB)	<15	~3(?)
IEEE 802.11 / RSS	Robotic-Based Location Sensing (Rice)	<10	~1.5
BT / CWPS	BlueSoft (Commercial)	<30	1
5.8GHz / RFID tags	PinPoint/ WhereNet	120	1~3
RSS	SpotON (U. Washington	<4	~1

Reinforced Node

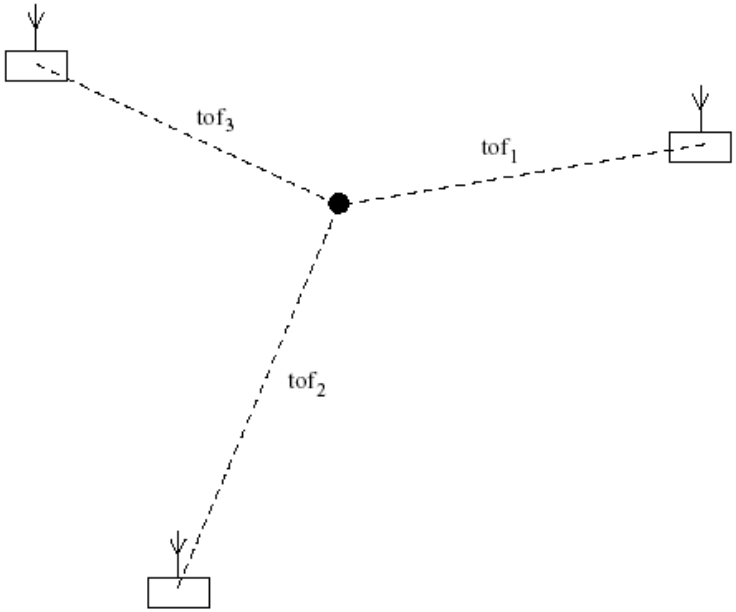
- Symmetrically damped package to sustain acceleration and speed

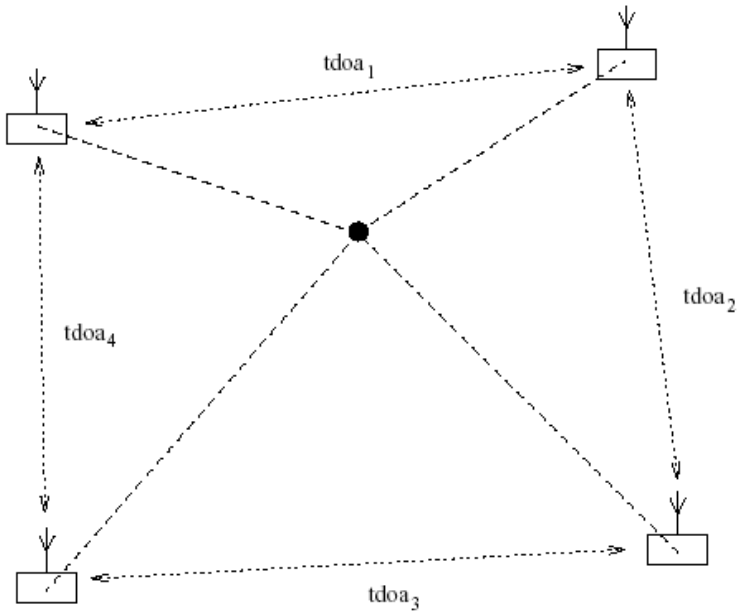


- All solid-state components, possibly a single chip
- Optical detectors mounted on shell
- Spherical antenna deposited on shell

LPS by Way of Reverse GPS

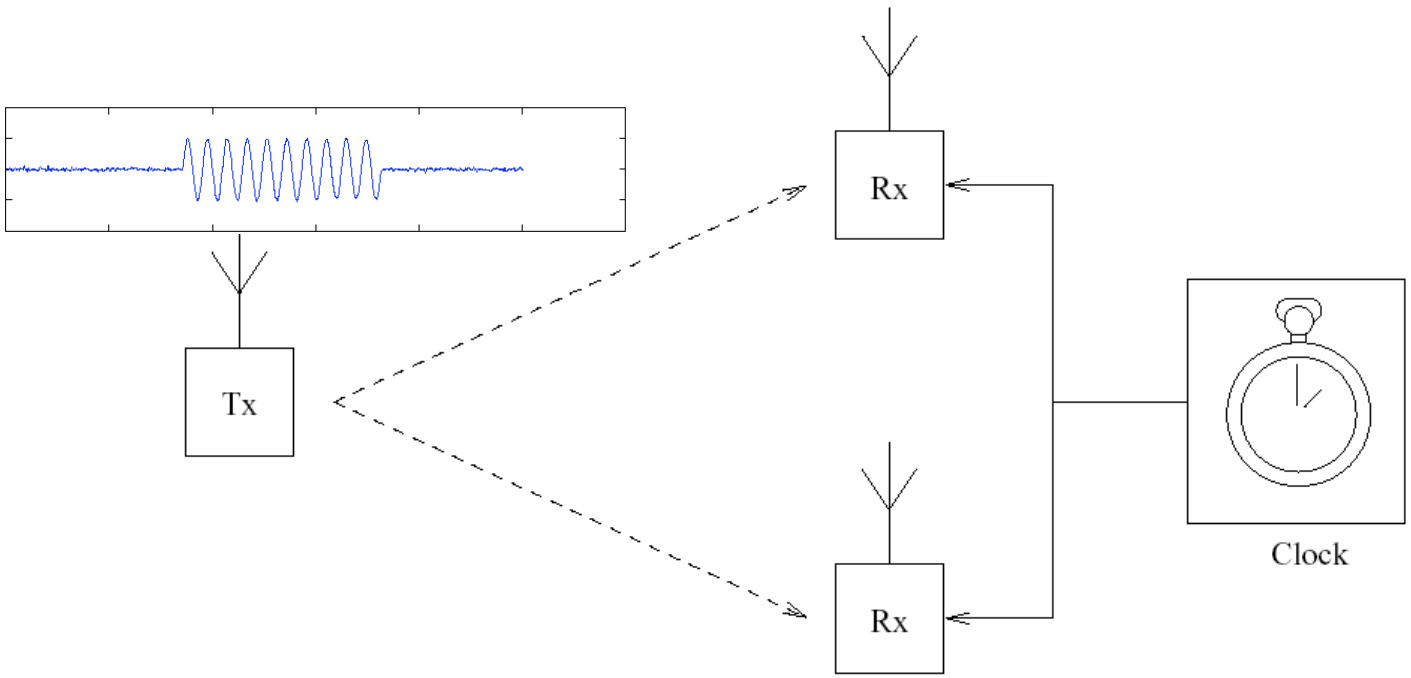
- **Position is computed using the difference in TOA**
  - **If emitters and receivers are synchronized at least 3 beacon stations are needed to compute position uniquely**
  - **Else, at least 4 beacons are needed**





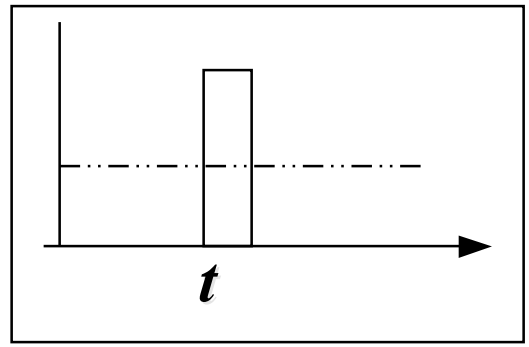
LPS by Way of Reverse-GPS (Cont.)

- Detect TOA of a train of M cycles originated by the node
- Problems
  - Exact pulse detection
  - TX, RX, and Channel distorsion, Multipath and fading



Pulse Detection

- **M = 1, classic method**
  - **Threshold → *t***
  - **Error: σ(d) = c/B**
  - **E.g.: B=192MHz → *σ(d) =1.6m***



- **M > 1,**
  - **Sample N times $x_R = [x_{R1},\ldots, x_{RN}]^T$**
  - **N samples are fitted to delayed transmitted signal** $A\sin(\omega t + \varphi)$
  - **A and φ are computed solving** $\hat{p} = (M^T M)^{-1} M^T x_R$

$$\mathrm{M} = \begin{bmatrix} \sin\omega t_1 & \cos\omega t_1 \\ \vdots & \vdots \\ \sin\omega t_N & \cos\omega t_N \end{bmatrix}$$

Error: $\sigma(d) \cong c\sqrt{\frac{1}{N\pi f}\frac{\sigma^2{}_n}{A^2}}$

E.g.: SNR=80dB, N=192,

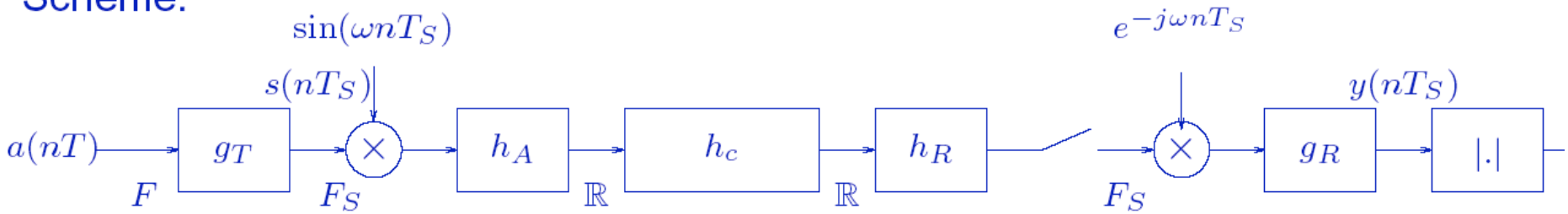
B=192MHz → *σ(d) =8cm*

But…

- Distorsion, multipath, fading prevent accurate detection of first pulse
- Possible solutions:
  - Use pseudorandom sequences
  - Finite Rate of Innovation concepts

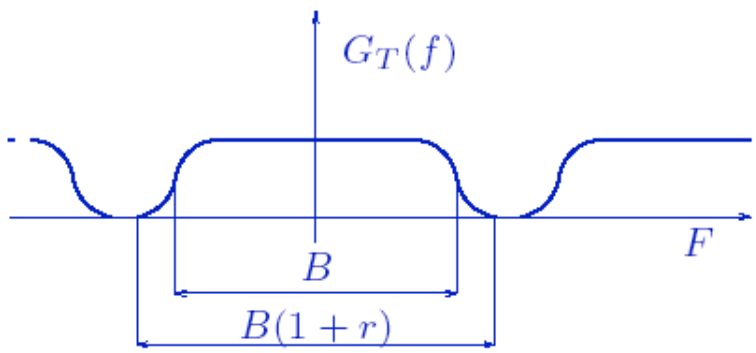
Pseudorandom Coding

Scheme:



Choose a(nT) s.t. $R_{aa}(nT) \approx \delta(nT)$

TX interpolator



Consecutive TOF signals can be resolved in 1/B seconds

E.g.: 10cm multipath resolution will require B=3GHz

Finite Rate of Innovation (FRI) and Evolution

- The method enables high resolution with fewer samples, provided one knows how many peaks P to expect
- If one underestimates P, then TOA may be inaccurate
- Else, spurious TOAs are added
- For infinite SNR, P can be estimated exactly by checking when matrix no longer well-conditioned
- For finite SNR boundary is fuzzy
- Possible solution:
  - Use a mix of classical and FRI detection
  - Reduce uncertainty of well-condition detection