GPS on Every Roof

Post-seismic building-wise damage identification system using sensor network equipped with affordable GPS

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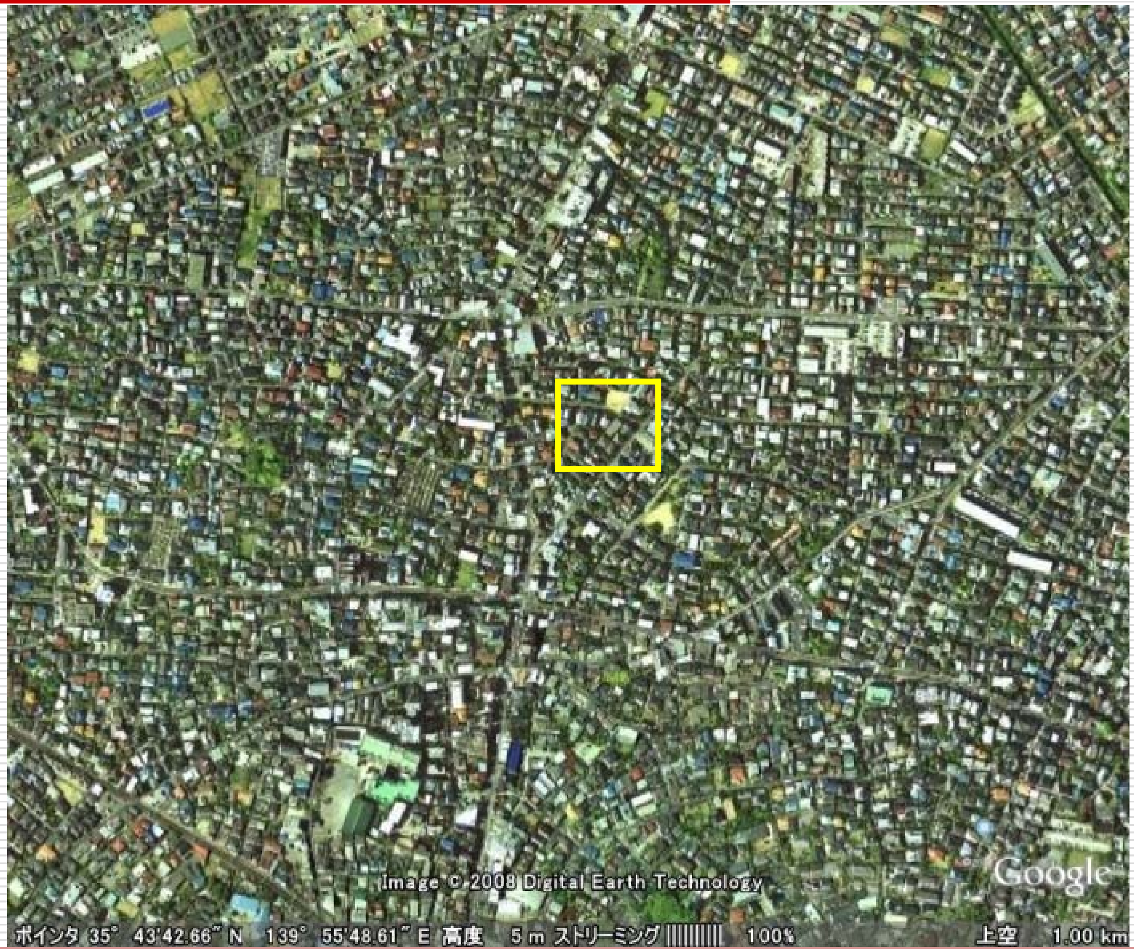
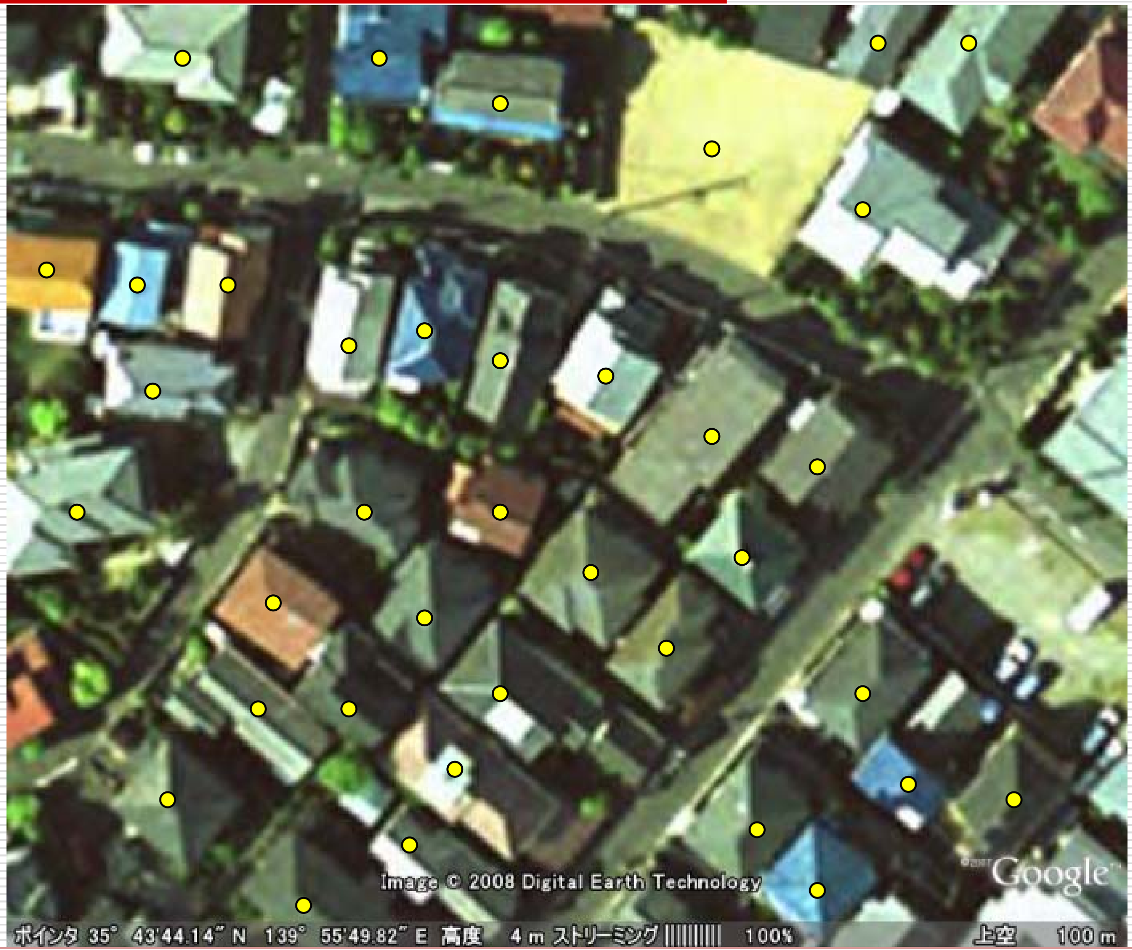
Target･･･buildings in densely populated area
Objective･･･identification of damage on each and every house right after earthquake



Typical example of densely populated area

Methodology:sensor node with GPS, Accelerometer and Wireless Communication on the roof of each and every house



○ Sensor node

Earthquake → activate GPS
→ on-board computation of the displacement of the roof

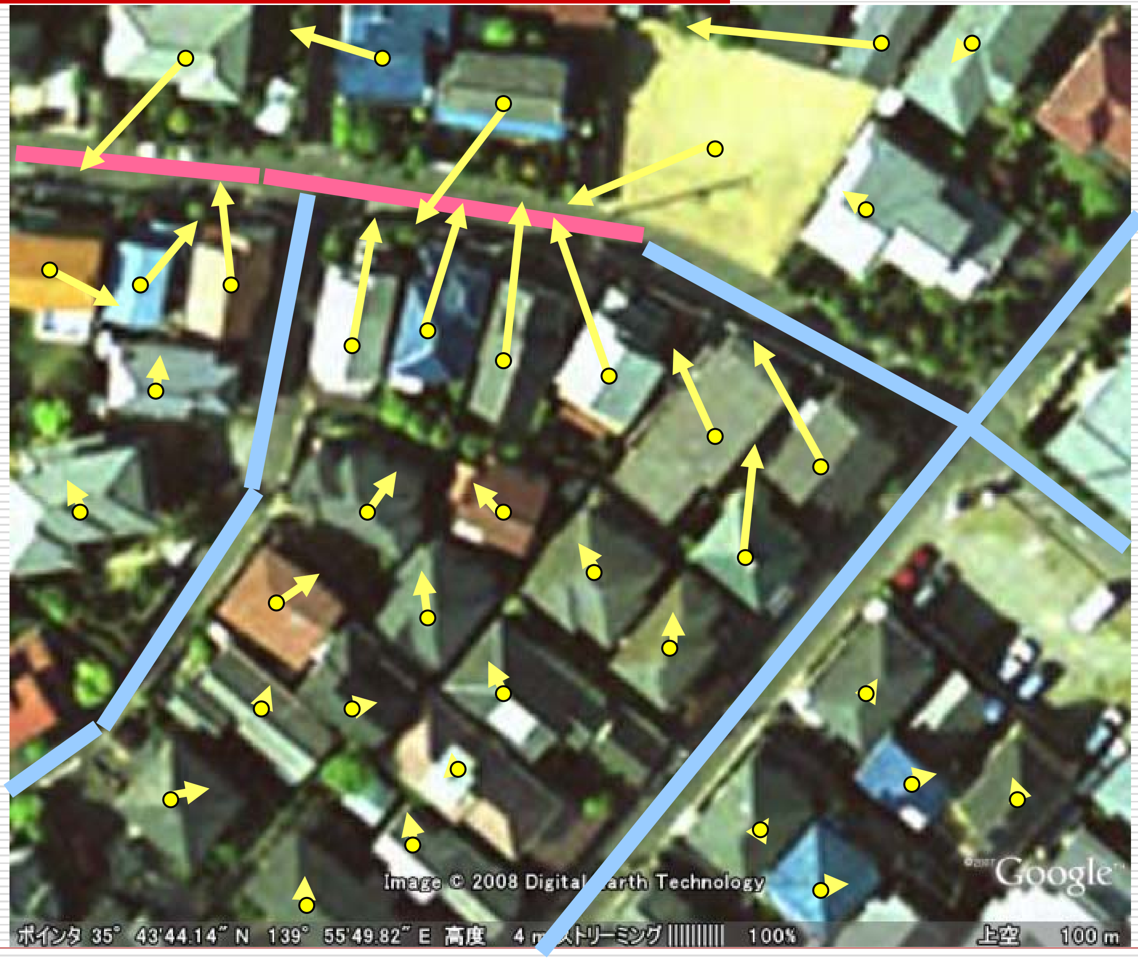
Optimum routing for gathering displacement data

Sensor node
Sensor node
Wireless communication route

Displacement of the roof of each building
→ Shown on GIS (collapse? direction?)

:No building collapsed :almost all collapsed

Details of building damage distribution
→ possible road closure can be shown on GIS



:Accessible :Road closed (with high possibility)

Straightforward application Why nobody has ever done it?

- GPS：accuracy, reliability, cost
  - GPS with high accuracy = high cost
  - Cheap GPS: localization accuracy =10m
- Sensor Network: reliability

  energy consumption
  - Commercial sensor network platform: short range communication, many packet loss
  - GPS+Sensor Network=too energy hungry

cost, accuracy, reliability ⇒ out of option

Seeds for making it possible

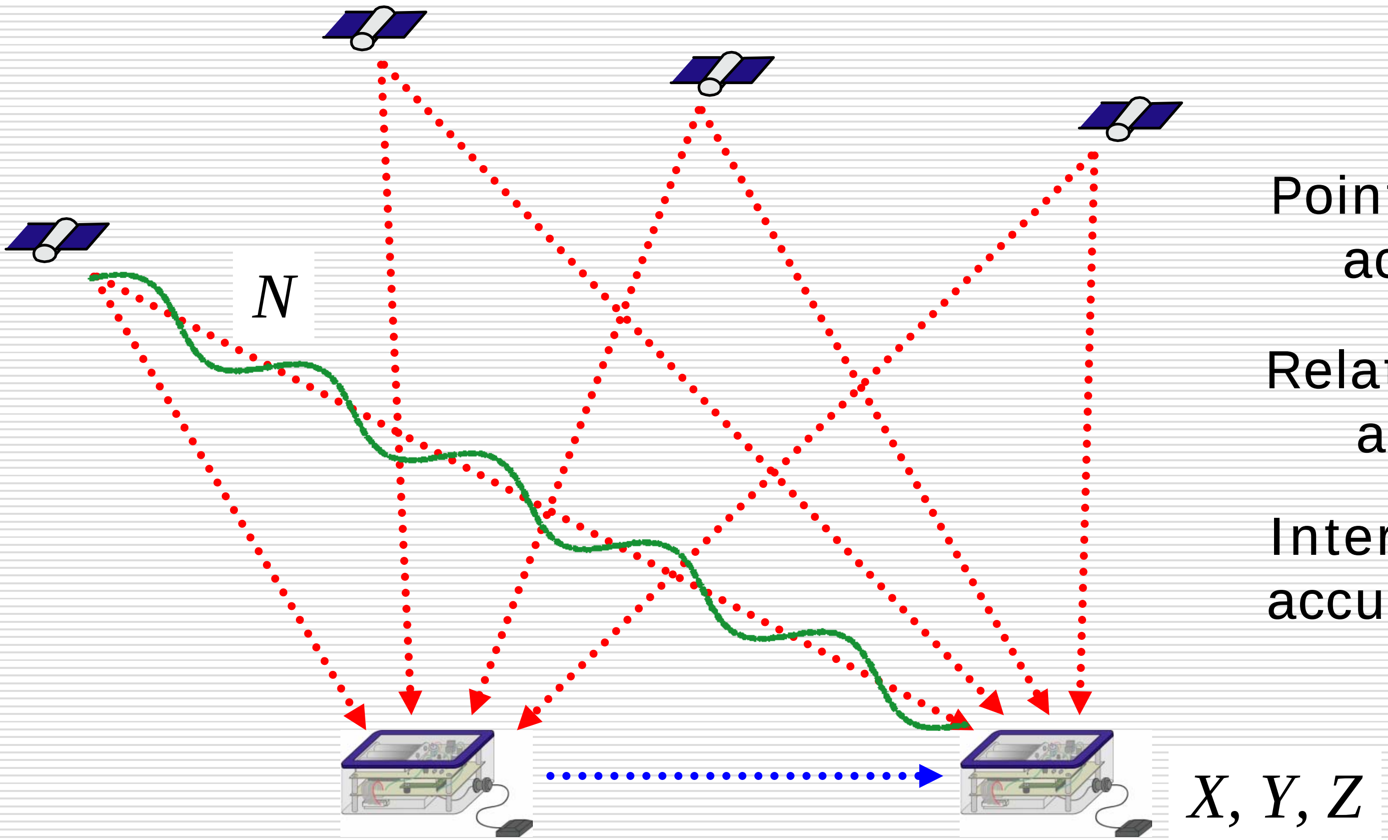
- In-house tools
  - GPS+Sensor Network
    - price, power, communication ･･･ no way! no way?
  - GPS localization algorithm (low-cost device, high accuracy)
    - Analysis on carrier phase
    - strong assumption based on “what is a building?”
- Building-to-land ratio, floor space index

  ･･･ if we see the city from the sky?

Details of “In-house tools” Affordable GPS with high accuracy

- Interferometric localization using raw data from GPS core
  - To reduce the cost and enhance the accuracy
    - Do not consider GPS as a commercial black box
- Integer ambiguity, cycle slip
  - Stable localization using an antenna for vehicle navigation which is known to be susceptible to multi path noise
    - Quasi-static assumption(buildings do not run!)
- Reduction of data
  - Inevitable for using GPS on sensor network
    - Keep minimum & throw away anything else

Interferometric localization(1)
Phase Difference → Vector between nodes



Point positioning:
accuracy≒30m

Relative positioning:
accuracy≒3m

Interferometric:
accuracy≒ a few cm

N.xxx, we measure 0.xxx can not measure N
→ Integer ambiguity

Interferometric Localization(2)
How to remove integer ambiguity?

$$U_j^k(t) = \rho_j^k(t)/\lambda + N_j^k + \cancel{\Delta t^k} + \Delta t_j - \cancel{\Delta_{ion,j}^k} + \cancel{\Delta_{trop,j}^k} + \Delta_{ant,j}^k + \varepsilon$$

Single difference

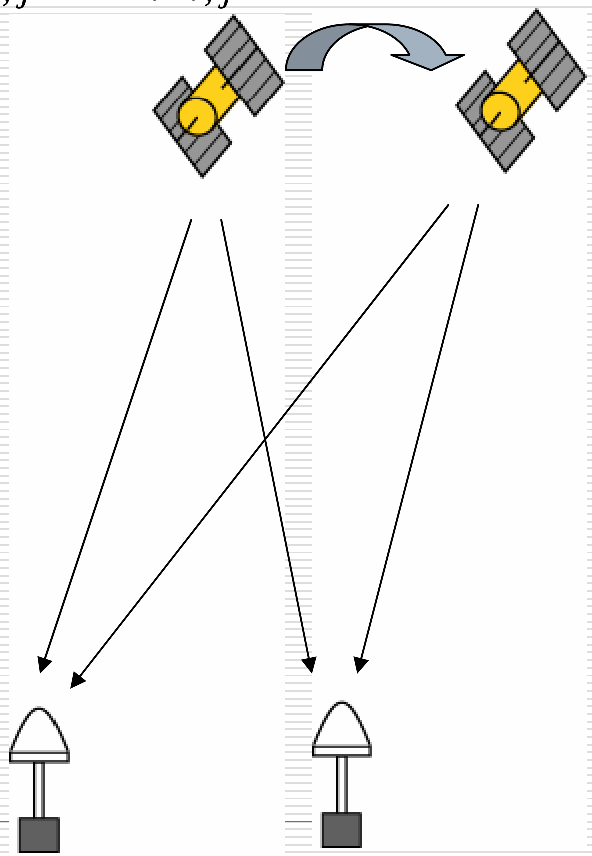
$$U_{ij}^k \equiv U_i^k - U_j^k$$

$$U_{ij}^k(t) = \rho_{ij}^k(t)/\lambda + N_{ij}^k + \cancel{\Delta t_{ij}} + \Delta_{ant,ij}^k + \varepsilon$$

Double difference

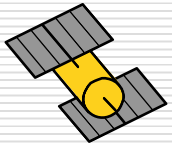
$$U_{ij}^{kl} \equiv U_i^k - U_i^l - (U_j^k - U_j^l)$$

$$U_{ij}^{kl}(t) = \rho_{ij}^{kl}(t)/\lambda + N_{ij}^{kl} + e_{ij}^{kl}(t)$$



Use all data from moving GPS satellites
→ Have to track GPS satellites for a while

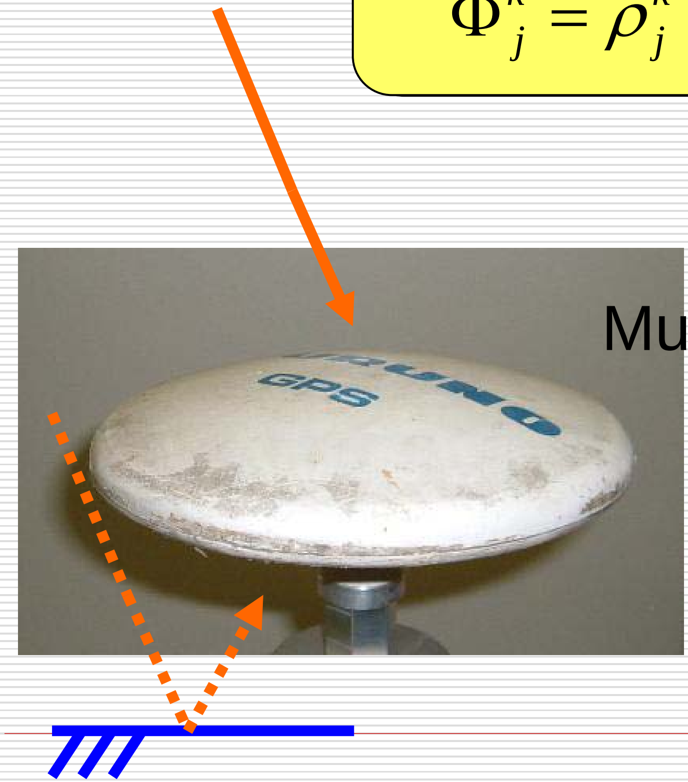
Patch antenna for vehicle navigation
Multi Path Noise and Cycle Slip



Carrier Phase :

$$\Phi_j^k = \rho_j^k / \lambda + N_j^k + \Delta_{ant,j}^k + \varepsilon$$

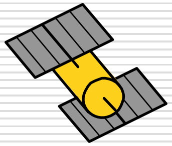
Multi-path noise



GPS antenna

Patch antenna

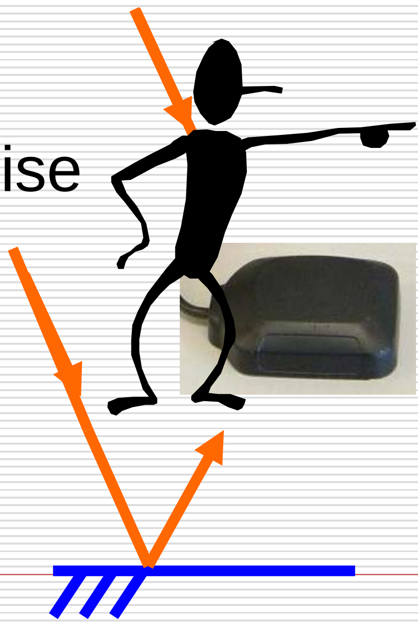
Patch antenna for vehicle navigation Multi Path Noise and Cycle Slip



Carrier Phase :

$$\Phi_j^k = \rho_j^k / \lambda + N_j^k + \Delta_{ant,j}^k + \varepsilon$$

Cycle slip ⇦ Multi-path noise

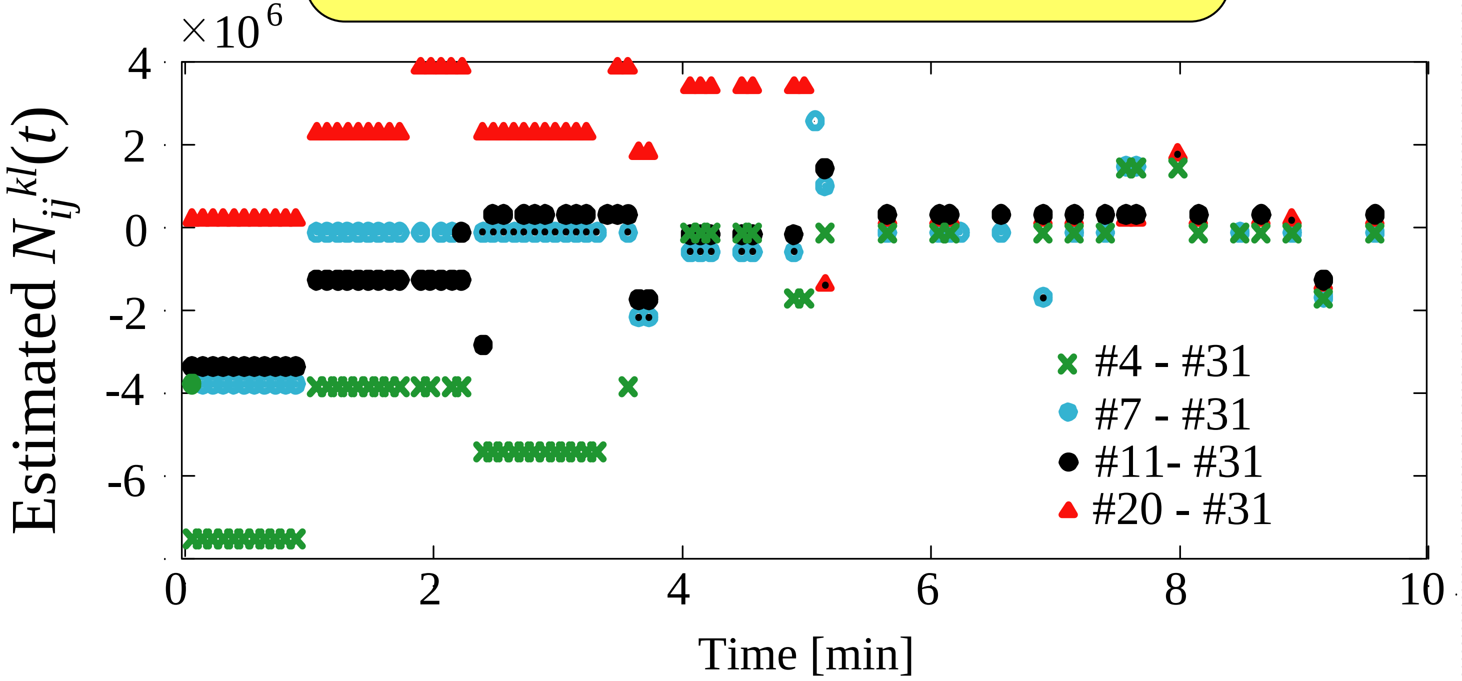


Patch antenna

Example of Cycle Slip

Integer bias :

$$N_{ij}^{kl}(t) = \Phi_{ij}^{kl}(t) - \rho_{ij}^{kl}(t)/\lambda$$



Quasi-static assumption (Buildings do not run!)

$$N_{ij}^{kl} = \Phi_{ij}^{kl}(t) - \rho_{ij}^{kl}(t)/\lambda$$

⇩

$$N_{ij}^{kl} = \Phi_{ij}^{kl}(t) - \overline{\rho}_{ij}^{kl}(t)/\lambda - \frac{1}{\lambda}\left[\frac{\partial \rho_{ij}^{kl}(t)}{\partial x}\Delta x + \frac{\partial \rho_{ij}^{kl}(t)}{\partial y}\Delta y + \frac{\partial \rho_{ij}^{kl}(t)}{\partial z}\Delta z\right]$$

constant

Linear w.r.t. time t

⇩

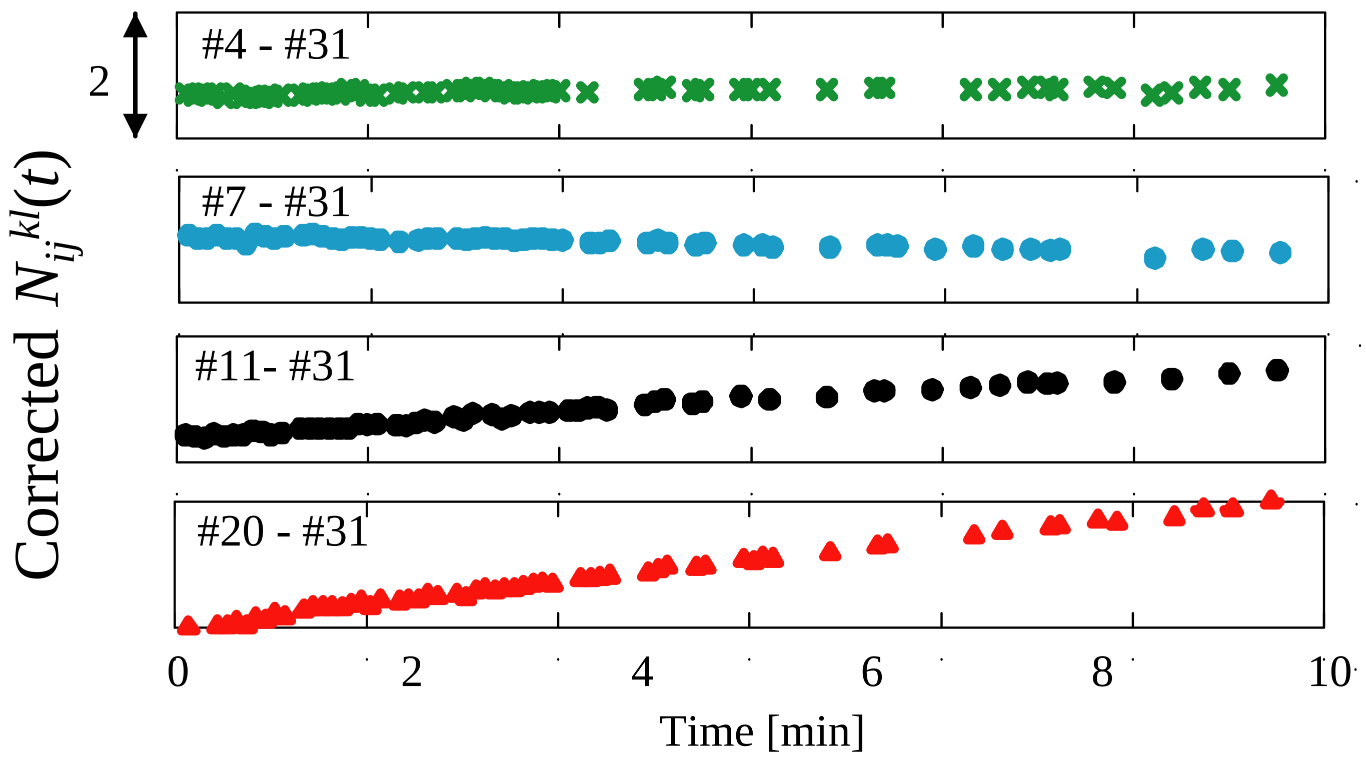
$$N(t) = at + b$$

Determine slope a and interception b

$$\left| N_{ij}^{kl} - N(t + \Delta t) \right| < 1/4$$

Correct N_{ij}^{kl}

Cycle Slip hopping in the order of 10^6 is suppressed



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For
Reliable communication＋low power consumption

- Amount of information: as small as possible

⇩

- By the improvement of localization algorithm

Default 266 byte/sec ⇨ Reduced to 29 byte/sec

- Max. power consumption 0.5Watt

Whole 1 day operation with AC power supply
＝100Watt lamp turned on for 7minutes
Continuous use on a rechargeable Li-ion battery 6～10 hours

Experiment

- Fancy GPS antenna & Patch antenna for vehicle navigation

Data length [sec]	Success rate [%]	
	Su	**Pa**
30	70.8	83.0
60	89.3	94.5
180	99.3	99.8
300	99.9	100.0
600	100.0	100.0

Data length [sec]	Accuracy 2σ [cm]			
	Su		**Pa**	
	H	V	H	V
30	-	-	0.5	0.7
60	0.7	1.1	0.4	0.7
180	0.6	1.0	0.4	0.6
300	0.6	0.9	0.4	0.5
600	0.4	0.7	0.3	0.5

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Yanaka, Nezu area (downtown close to UT)

Dense distribution of small houses
and low rise (5-10 story) apartments

Yanaka, Nezu area (downtown close to UT)

Very old wooden house at the entrance of narrow passage･･･

Yanaka, Nezu area (downtown close to UT)

Scraped sky＋no line of sight on the road
(Worst for GPS and wireless communication)

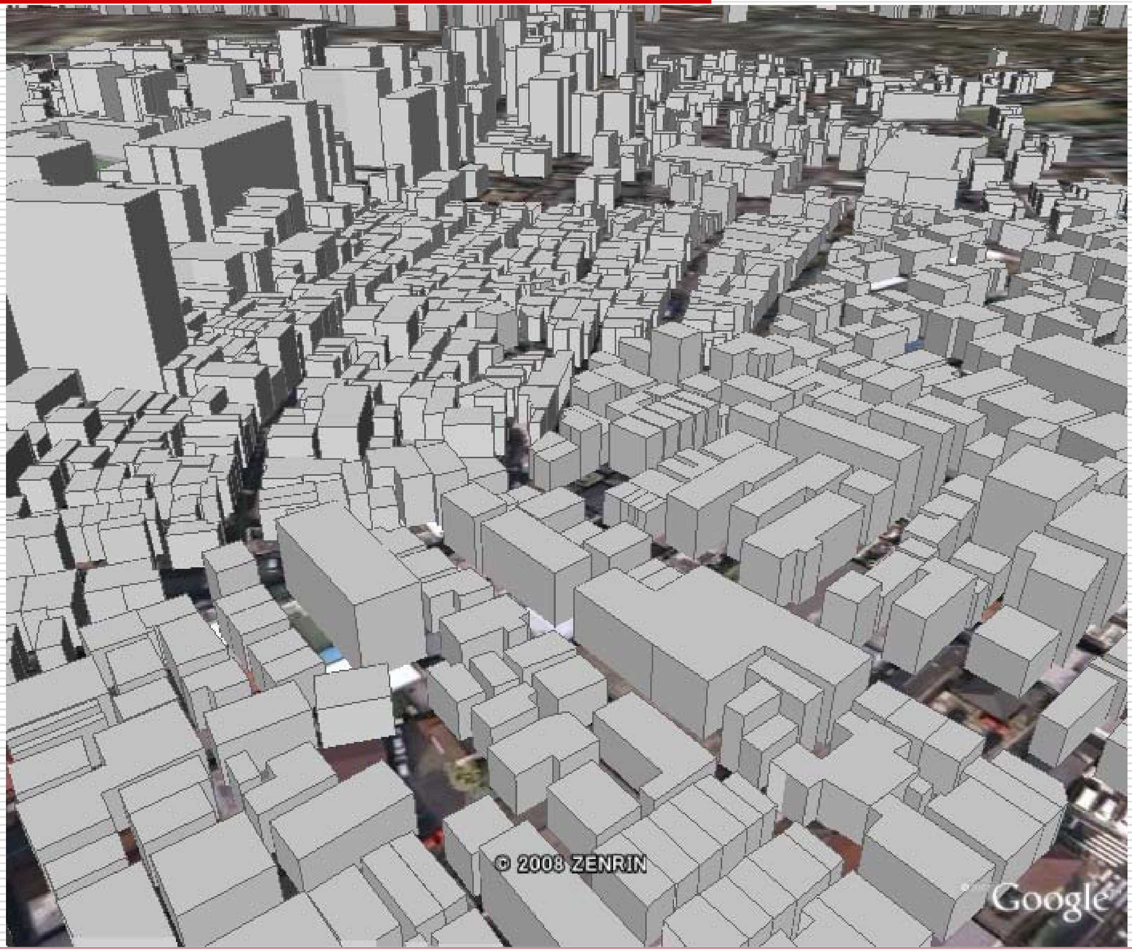
Yanaka, Nezu area (downtown close to UT)

No line of sight on the road, but on the roof?

Yanaka, Nezu are
(downtown close

Tall buildings=disturbing the sight? watchtower?

Yanaka, Nezu area (downtown close to UT)



Top view･･･almost flat, tall buildings here and there

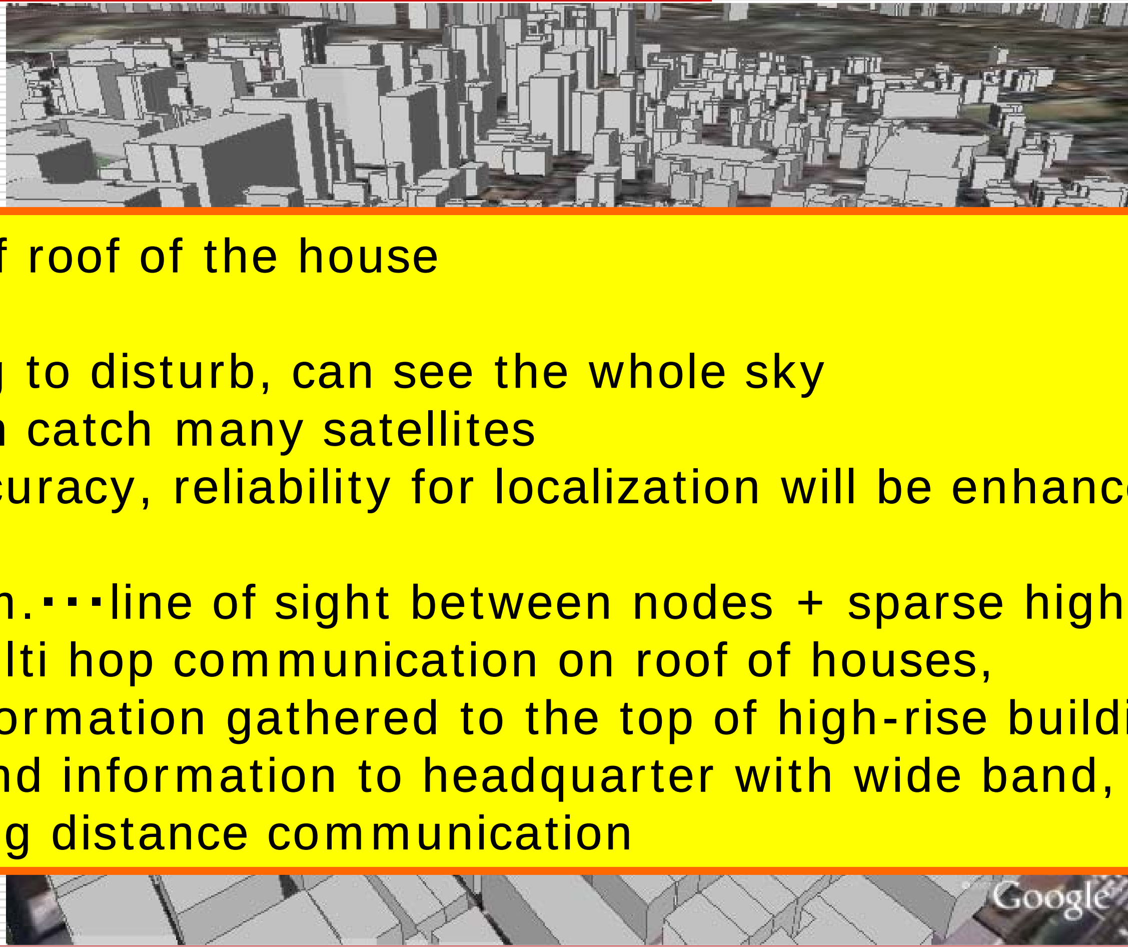
Yanaka, Nezu area (downtown close to UT)

Building-to-land ratio
Floor-space index
:kept uniform for an area.

Height of the buildings is kept almost constant

Top view･･･almost flat, tall buildings here and there

Yanaka, Nezu area (downtown close to UT)



On the level of roof of the house

GPS･･･nothing to disturb, can see the whole sky

→ can catch many satellites

→ accuracy, reliability for localization will be enhanced

Wireless comm.･･･line of sight between nodes + sparse high rise buildings

→ multi hop communication on roof of houses,
information gathered to the top of high-rise buildings,
send information to headquarter with wide band,
long distance communication

If “GPS on Every Roof” is realized

- First case for using large scale sensor network for society
  - GPS localization to solve dilemma between cost and accuracy
    - Positioning with mm accuracy for $800 (aiming at $100)
  - Sensor network with robust hardware as an infrastructure
    - No use for short range, ad-hoc, multi hop sensor network with packet loss.
    - Robust hardware + hierarchical control of communication
- Infrastructure of next generation
  - Current : skeleton(buildings), circulatory system(road, railway) Next: nervous system
    - Each building is equipped with sensor node with wireless communication
  - “GPS on Every Roof”=1st generation of infrastructure with the nervous system