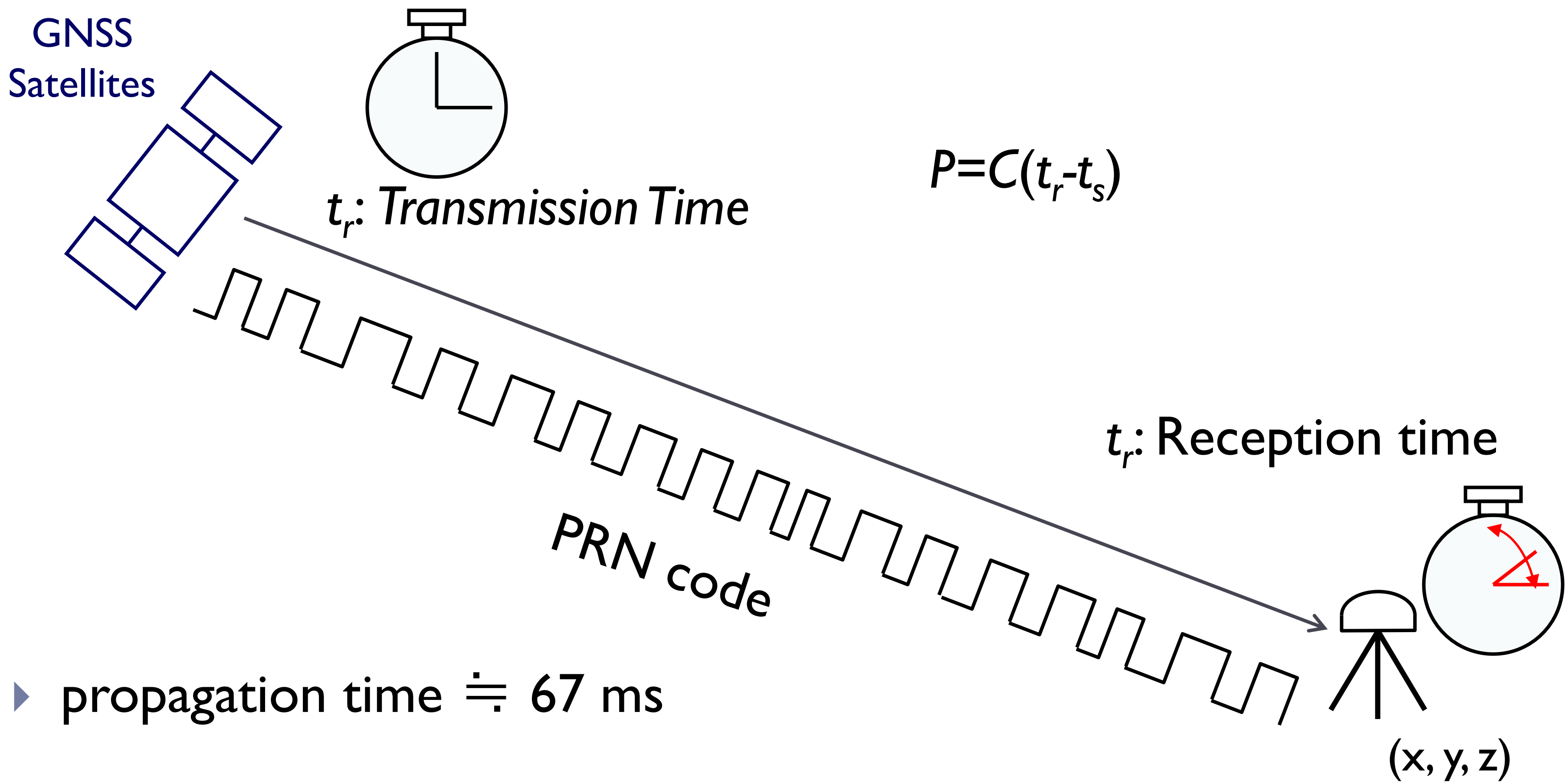
10: Positioning

Taro Suzuki

Pseudorange Calculation (1)

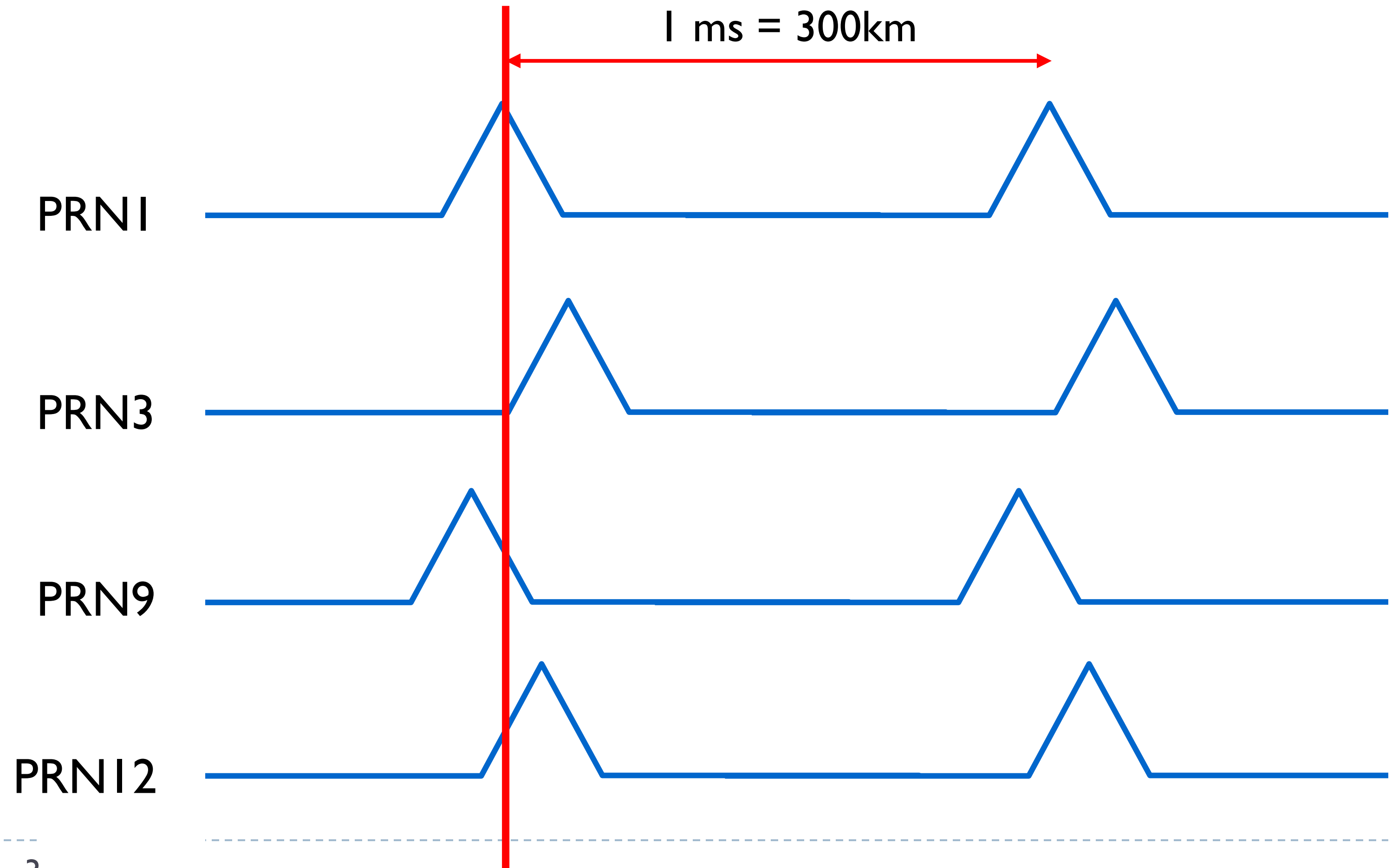
- Calculate distance based on difference between transmission time and reception time



- propagation time ≒ 67 ms

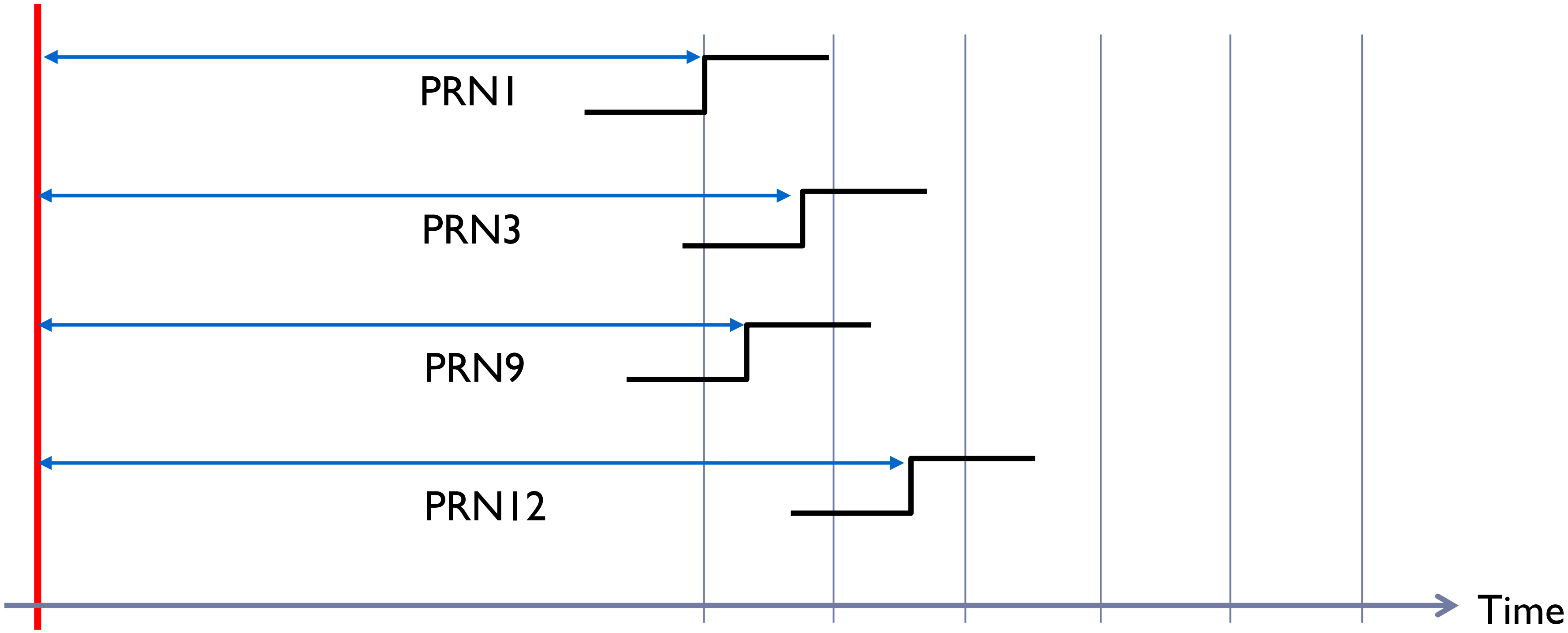
Pseudorange Calculation (2)

- The code phase shift for each satellite is the relative difference in distance

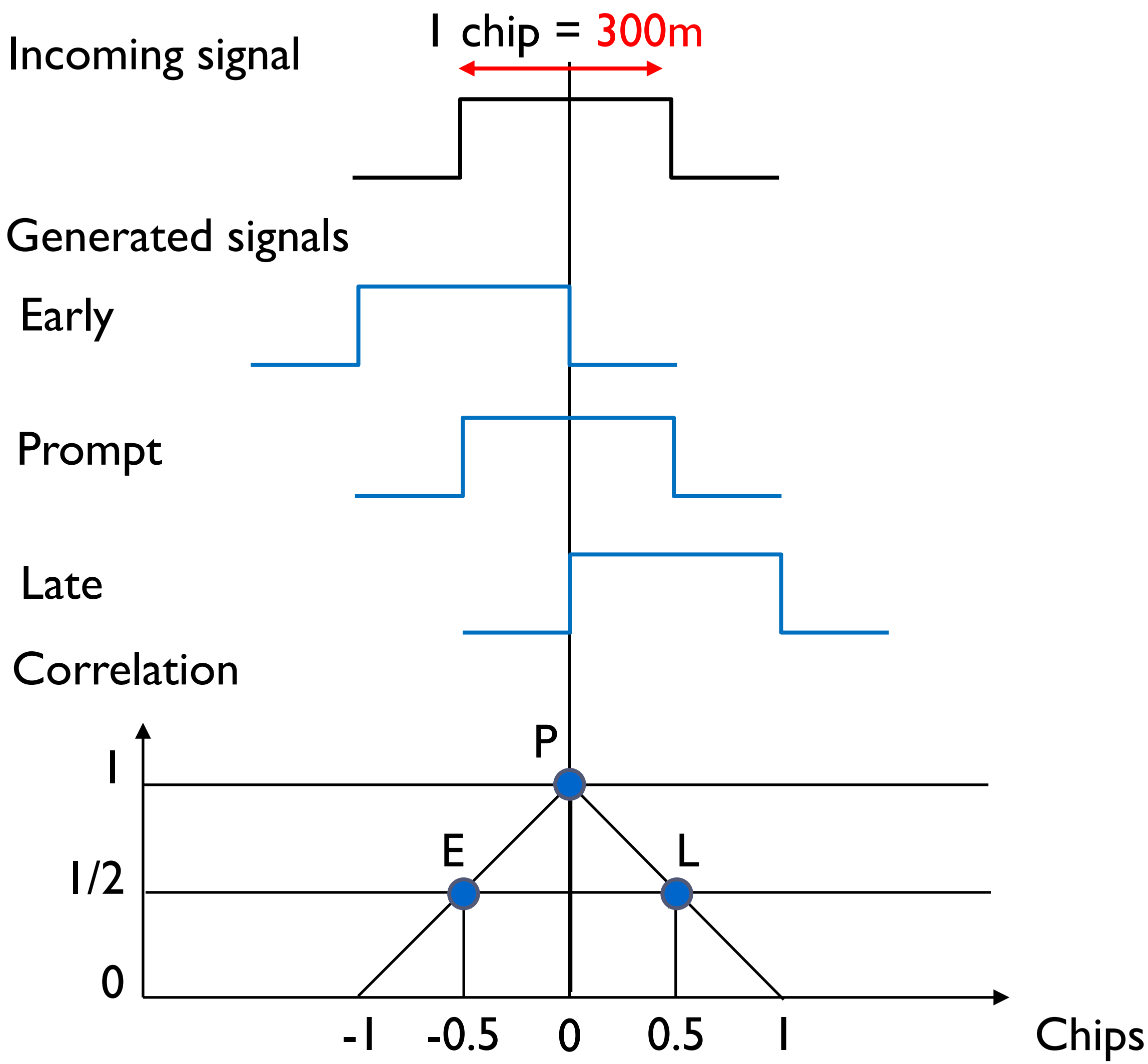


Pseudorange Calculation (2)

- Find the time difference at the beginning of the subframe
- Time synchronization of less than 1 ms is adjusted by E-P-L correlator



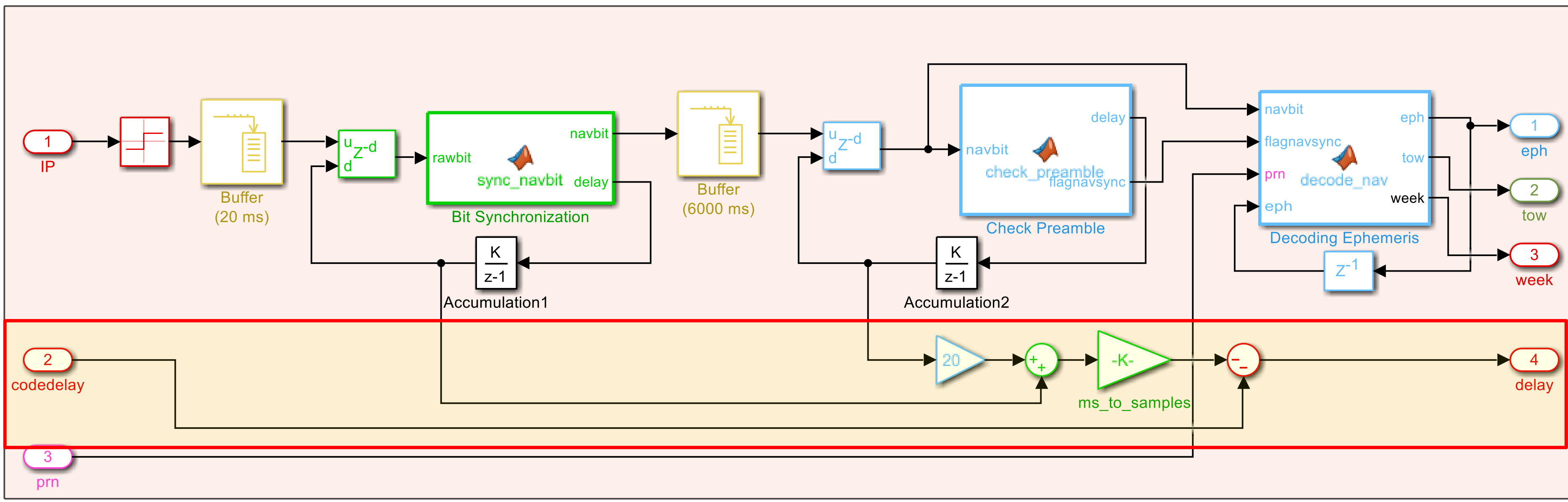
Pseudorange Calculation (3)



Delay Computation

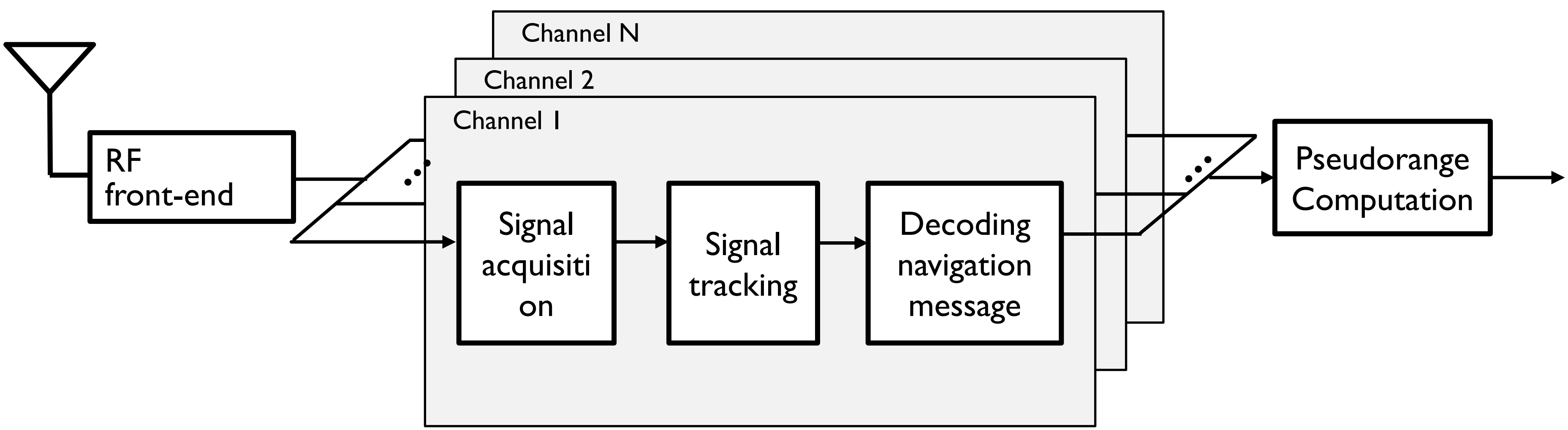
- Initial code phase + remcode
- Bit synchronization + subframe synchronization

Decoding



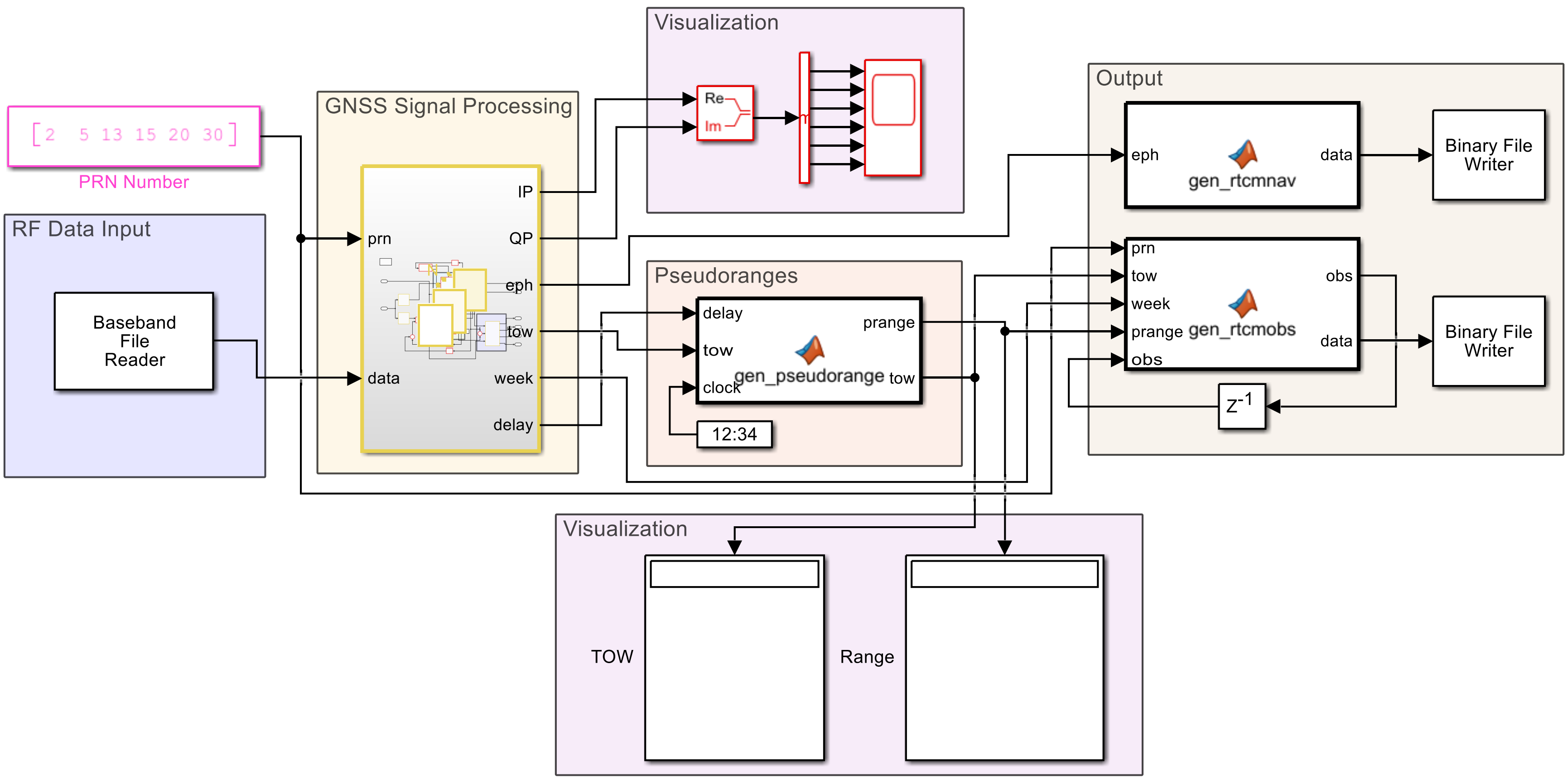
Parallel processing for each satellite signal

- Calculate the pseudoranges from the delay information of each channel at a certain timing of the receiver
- Aggregate the results of satellite signal tracking executed in parallel and calculate the range



Simulink Model

- Use of For Each Subsystem
  - Parallelized signal processing (acquisition, tracking, decoding)



RINEX

- <u>Receiver Independent Exchange Format</u>
  - ASCII
  - Pseudorange, carrier phase, Doppler, Signal-to-Noise ratio

```
     3.03           OBSERVATION DATA    M: Mixed            RINEX VERSION / TYPE
RTKCONV 2.4.3 b34                       20220806 173351 UTC PGM / RUN BY / DATE
                                                            MARKER NAME
                                                            MARKER NUMBER
                                                            MARKER TYPE
                                                            OBSERVER / AGENCY
                                                            REC # / TYPE / VERS
                                                            ANT # / TYPE
        0.0000        0.0000        0.0000                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G    1 C1C                                                  SYS / # / OBS TYPES
  2022    08    05    06    48   36.9000000     GPS         TIME OF FIRST OBS
  2022    08    05    06    49   18.9000000     GPS         TIME OF LAST OBS
  0                                                         GLONASS SLOT / FRQ #
 C1C     0.000 C1P     0.000 C2C     0.000 C2P     0.000    GLONASS COD/PHS/BIS
                                                            END OF HEADER
> 2022 08 05 06 48 42.0000000  0  6
G02  20385887.144
G05  19637026.467
G13  19162987.397
G15  20929127.718
G20  19759870.608
G30  21472839.361
```

RTCM

- Format for real-time GNSS communication
  - Binary
  - Originally a data format for differential correction, RTCM MSM, a format for communicating GNSS observations, was also specified

```
  TYPE          : GPS    GLONASS Galileo  QZSS    BDS     SBAS    NavIC
---------------------------------------------------------------------------
OBS COMP L1     : 1001~  1009~    -        -       -       -       -
    FULL L1     : 1002   1010     -        -       -       -       -
    COMP L1L2   : 1003~  1011~    -        -       -       -       -
    FULL L1L2   : 1004   1012     -        -       -       -       -

NAV             : 1019   1020    1045**   1044    1042     -      1041
                    -      -     1046**    -        63*    -       -

MSM  1          : 1071~  1081~   1091~    1111~   1121~   1101~   1131~
     2          : 1072~  1082~   1092~    1112~   1122~   1102~   1132~
     3          : 1073~  1083~   1093~    1113~   1123~   1103~   1133~
     4          : 1074   1084    1094     1114    1124    1104    1134
     5          : 1075   1085    1095     1115    1125    1105    1135
     6          : 1076   1086    1096     1116    1126    1106    1136
     7          : 1077   1087    1097     1117    1127    1107    1137

SSR ORBIT       : 1057   1063    1240*    1246*   1258*    -       -
    CLOCK       : 1058   1064    1241*    1247*   1259*    -       -
    CODE BIAS   : 1059   1065    1242*    1248*   1260*    -       -
    OBT/CLK     : 1060   1066    1243*    1249*   1261*    -       -
    URA         : 1061   1067    1244*    1250*   1262*    -       -
    HR-CLOCK    : 1062   1068    1245*    1251*   1263*    -       -
    PHAS BIAS   :   11*    -       12*      13*     14*    -       -

ANT/RCV INFO    : 1007   1008    1033
STA POSITION    : 1005   1006

PROPRIETARY     : 4076 (IGS)
---------------------------------------------------------------------------
                  (* draft, ** 1045:F/NAV,1046:I/NAV, ~ only encode)

for MSM observation data with multiple signals for a frequency,
a signal is selected according to internal priority. to select
a specified signal, use the input options.

RTCM 3 message format:
  +----------+--------+-----------+--------------------+----------+
  | preamble | 000000 |  length   |    data message    |  parity  |
  +----------+--------+-----------+--------------------+----------+
  |<-- 8 --->|<- 6 -->|<-- 10 --->|<--- length x 8 --->|<-- 24 -->|

-------------------------------------------------------------------*/
```

Positioning Computation (1)

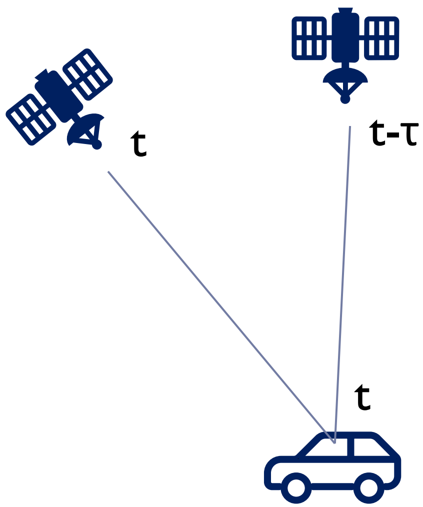
$$\rho_c^{(k)} = r^{(k)} + c\delta t_u + \tilde{\varepsilon}_\rho^{(k)}$$

$$\begin{cases} r^{(k)} = \sqrt{(x^{(k)}-x)^2 + (y^{(k)}-y)^2 + (z^{(k)}-z)^2} = \left\| \mathbf{x}^{(k)} - \mathbf{x} \right\| \\ b = c\delta t_u \end{cases}$$

$$\rho_c^{(k)} = \left\| \mathbf{x}^{(k)} - \mathbf{x} \right\| + b + \tilde{\varepsilon}_\rho^{(k)}$$

Satellite position at t-τ

$$\mathbf{x}^{(k)} = \begin{bmatrix} \cos\omega_E\tau & \sin\omega_E\tau & 0 \\ -\sin\omega_E\tau & \cos\omega_E\tau & 0 \\ 0 & 0 & 1 \end{bmatrix} \tilde{\mathbf{x}}^{(k)}$$



$\rho_c^{(k)}$	Compensated Pseudorange
$r^{(k)}$	True range
δt_u	Receiver clock error
$\tilde{\varepsilon}_\rho^{(k)}$	Pseudorange noise
$\mathbf{x}^{(k)}$	Satellite position at t
$\tilde{\mathbf{x}}^{(k)}$	Satellite position at t-τ
$\mathbf{x}$	User position
b	Receiver clock error [m]
ω_E	Earth rotation rate
τ	Propagation time

Positioning Computation (2)

$$\rho_c^{(k)} = \left\| \mathbf{x}^{(k)} - \mathbf{x} \right\| + b$$

Linearize the observed equations for the number of and find the correct solution by iteration

$$\mathbf{x} = \mathbf{x}_0 + \delta\mathbf{x} = \begin{pmatrix} x_0 + \delta x \\ y_0 + \delta y \\ z_0 + \delta z \end{pmatrix}$$

$$b = b_0 + \delta b$$

$$\begin{aligned} \delta\rho^{(k)} &= \rho_c^{(k)} - \rho_0^{(k)} \\ &= \left\| \mathbf{x}^{(k)} - \mathbf{x}_0 - \delta\mathbf{x} \right\| - \left\| \mathbf{x}^{(k)} - \mathbf{x}_0 \right\| + (b - b_0) + \tilde{\varepsilon}_\rho^{(k)} \\ &\cong -\frac{(\mathbf{x}^{(k)} - \mathbf{x}_0)}{\left\| \mathbf{x}^{(k)} - \mathbf{x}_0 \right\|} \cdot \delta\mathbf{x} + \delta b + \tilde{\varepsilon}_\rho^{(k)} \\ &= -\mathbf{l}^{(k)} \cdot \delta\mathbf{x} + \delta b + \tilde{\varepsilon}_\rho^{(k)} \end{aligned}$$

$$\mathbf{l}^{(k)} = \begin{pmatrix} \alpha^{(k)} \\ \beta^{(k)} \\ \gamma^{(k)} \end{pmatrix} = \begin{pmatrix} \dfrac{x^{(k)} - x_0}{R_0^k} \\ \dfrac{y^{(k)} - y_0}{R_0^k} \\ \dfrac{z^{(k)} - z_0}{R_0^k} \end{pmatrix}$$

$$R_0^{(k)} = \sqrt{(x^{(k)} - x_0)^2 + (y^{(k)} - y_0)^2 + (z^{(k)} - z_0)^2}$$

Positioning Computation (3)

$$\delta\boldsymbol{\rho} = \begin{bmatrix} \delta\rho^{(1)} \\ \delta\rho^{(2)} \\ \vdots \\ \delta\rho^{(K)} \end{bmatrix} = \begin{bmatrix} (-\mathbf{l}^{(1)})^T & 1 \\ (-\mathbf{l}^{(2)})^T & 1 \\ \vdots & \vdots \\ (-\mathbf{l}^{(K)})^T & 1 \end{bmatrix} \begin{bmatrix} \delta\mathbf{x} \\ \delta b \end{bmatrix} + \tilde{\boldsymbol{\varepsilon}}_\rho$$

$$\delta\boldsymbol{\rho} = \mathbf{G}\begin{bmatrix} \delta\mathbf{x} \\ \delta b \end{bmatrix} + \tilde{\boldsymbol{\varepsilon}}_\rho$$

$$\mathbf{G} = \begin{bmatrix} -\alpha^{(1)} & -\beta^{(1)} & -\gamma^{(1)} & 1 \\ -\alpha^{(2)} & -\beta^{(2)} & -\gamma^{(2)} & 1 \\ \vdots & \vdots & \vdots & 1 \\ -\alpha^{(K)} & -\beta^{(K)} & -\gamma^{(K)} & 1 \end{bmatrix}$$

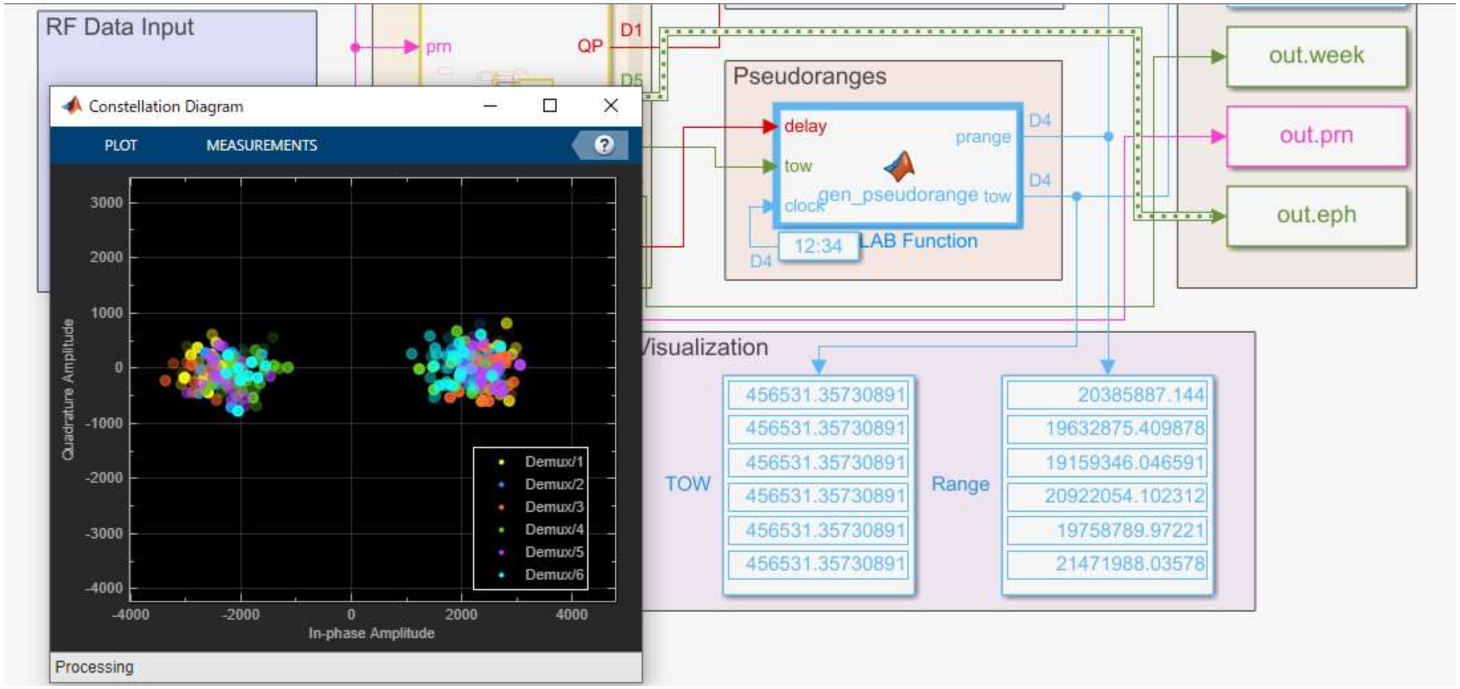
least-squares solution $\begin{bmatrix} \delta\hat{\mathbf{x}} \\ \delta\hat{b} \end{bmatrix} = (\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}^T\delta\boldsymbol{\rho}$

Recalculate the first estimate corrected by the above solution. If the estimates of the next calculation converge, the calculation is completed.

$$\hat{\mathbf{x}} = \mathbf{x}_0 + \delta\hat{\mathbf{x}}$$
$$\hat{b} = b_0 + \delta\hat{b}$$

Exercise 1: Positioning using RTKLIB (1)

- Simulink
  - **/10_Positioning + SDR_Application/simulink/Ex1/sdr_positioning.slx**



- <u>Pseudoranges are saved to MATLAB Workspace</u>

Exercise 1: Positioning using RTKLIB (2)

- MATLAB
  - **/10_Positioning+SDR_Application/simulink/Ex1/run_gen_rinex.m**
  - Pseudoranges and time information is converted to RINEX file

sdr_obs.obs

```
     3.02           OBSERVATION DATA    G: GPS              RINEX VERSION / TYPE
                                        20220809 155724 UTC PGM / RUN BY / DATE
                                                            MARKER NAME
                                                            MARKER NUMBER
                                                            MARKER TYPE
                                                            OBSERVER / AGENCY
                                                            REC # / TYPE / VERS
                                                            ANT # / TYPE
        0.0000        0.0000        0.0000                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G    1 C1C                                                  SYS / # / OBS TYPES
  2022    08    05    06    48   47.9573097     GPS         TIME OF FIRST OBS
  2022    08    05    06    49   23.9573016     GPS         TIME OF LAST OBS
  0                                                         GLONASS SLOT / FRQ #
                                                            GLONASS COD/PHS/BIS
                                                            END OF HEADER
> 2022 08 05 06 48 47.9573097  0  6
G02  20385887.144
G05  19634375.952
G13  19160660.915
G15  20924612.079
G20  19759181.563
G30  21472290.224
> 2022 08 05 06 48 48.0573097  0  6
G02  20385887.144
G05  19634333.835
G13  19160622.307
G15  20924535.654
G20  19759168.656
G30  21472279.239
> 2022 08 05 06 48 48.1573096  0  6
G02  20385887.144
```

sdr_nav.nav

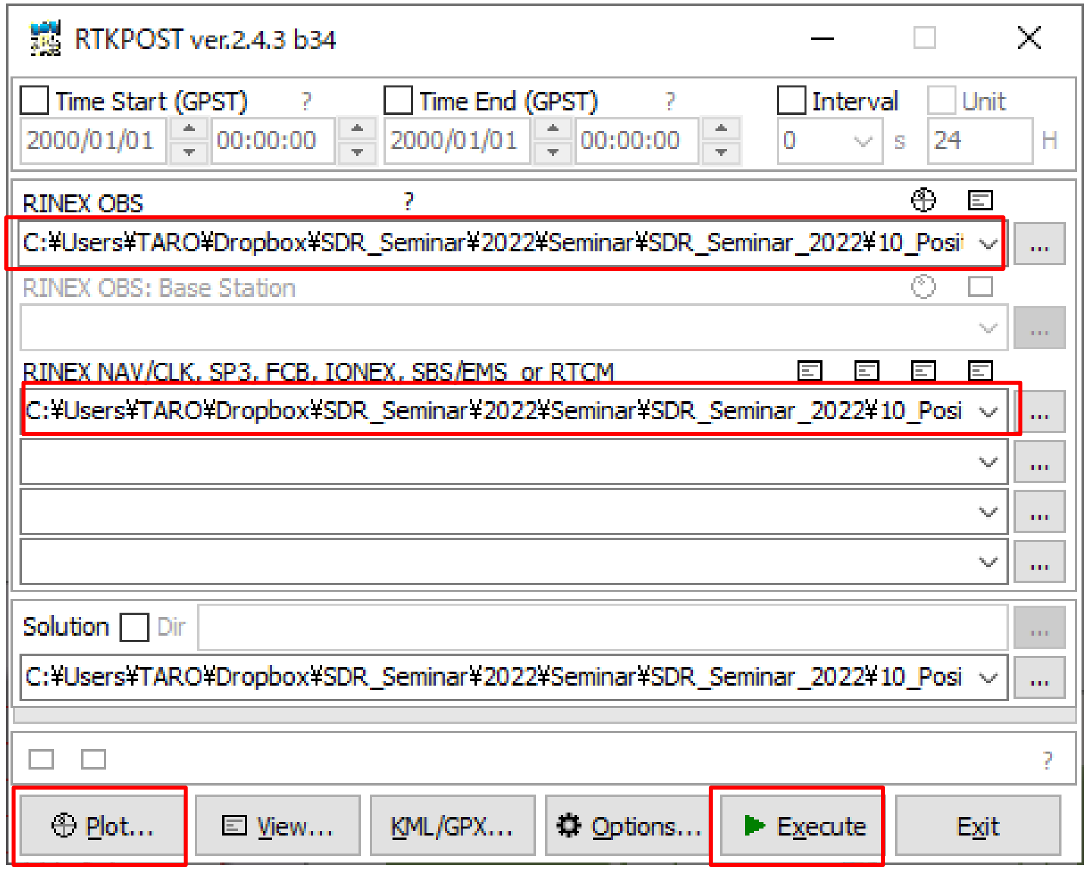
```
     3.02           N: GNSS NAV DATA    M: Mixed            RINEX VERSION / TYPE
                                        20220809 155724 UTC PGM / RUN BY / DATE
                                                            END OF HEADER
G02 2022 08 05 07 59 44 -.649891328067D-03  .909494701773D-12  .000000000000D+00
      .800000000000D+01 -.567812500000D+02  .439696886569D-08 -.134245450696D+01
     -.280886888504D-05  .199471334927D-01  .915862619877D-05  .515487974548D+04
      .460784000000D+06 -.335276126862D-06  .127323360928D+01  .342726707458D-06
      .966132581037D+00  .208343750000D+03 -.140052384930D+01 -.824070040111D-08
     -.167864135072D-09  .100000000000D+01  .222100000000D+04  .000000000000D+00
      .200000000000D+01  .000000000000D+00 -.172294676304D-07  .800000000000D+01
      .456546000000D+06  .000000000000D+00
G05 2022 08 05 08 00 00 -.917343422771D-04 -.136424205266D-11  .000000000000D+00
      .480000000000D+02 -.125625000000D+02  .451804533758D-08  .127297544227D+01
     -.659376382828D-06  .611729302909D-02  .811740756035D-05  .515376311874D+04
      .460800000000D+06 -.335276126862D-07  .235706787130D+01 -.447034835815D-07
      .961843973782D+00  .229406250000D+03  .107979299179D+01 -.812212403335D-08
      .255367779950D-09  .100000000000D+01  .222100000000D+04  .000000000000D+00
      .200000000000D+01  .000000000000D+00 -.111758708954D-07  .480000000000D+02
      .456546000000D+06  .000000000000D+00
G13 2022 08 05 08 00 00  .361989717931D-03  .716227077646D-11  .000000000000D+00
      .160000000000D+02 -.255625000000D+02  .445268547222D-08  .474524408406D+00
     -.140443444252D-05  .623134977650D-02  .781938433647D-05  .515367332649D+04
      .460800000000D+06 -.745058059692D-07 -.270109467665D+01  .912696123123D-07
      .969177497264D+00  .234468750000D+03  .920800360242D+00 -.804354933183D-08
     -.164649715464D-09  .100000000000D+01  .222100000000D+04  .000000000000D+00
      .200000000000D+01  .000000000000D+00 -.111758708954D-07  .160000000000D+02
      .456546000000D+06  .000000000000D+00
G15 2022 08 05 08 00 00 -.397786498070D-04  .306954461848D-11  .000000000000D+00
      .930000000000D+02 -.254375000000D+02  .542486882470D-08 -.505896645654D-01
```

Exercise 1: Positioning using RTKLIB (3)

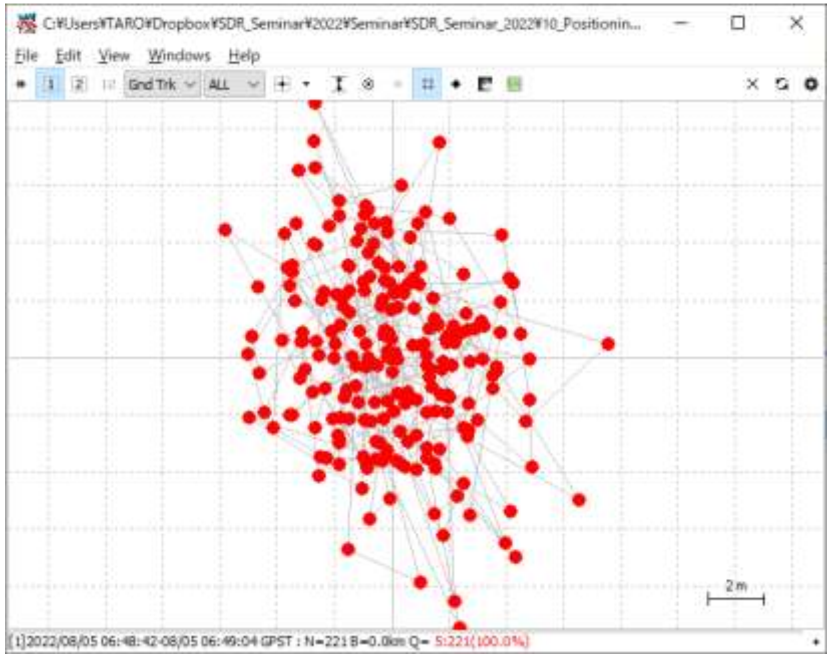
- Run **/rtklib/rtkpost.exe**

sdr_obs.obs

sdr_nav.nav



Exercise 1: Positioning using RTKLIB (4)



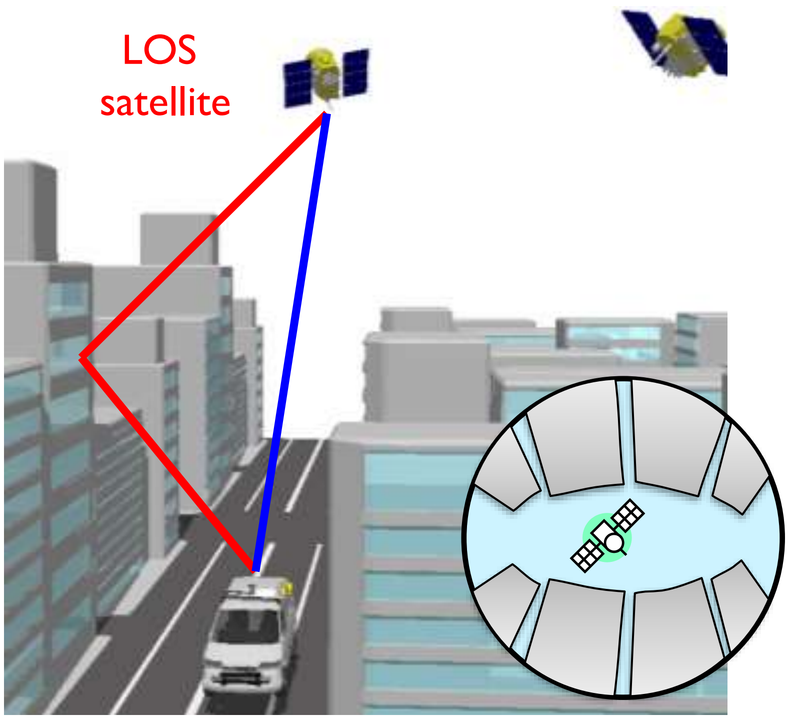
- Advanced challenge
  - Estimate position with RF data acquired by yourself!
  - Compare positioning results by changing the DLL noise bandwidth
  - Realtime processing using RTL-SDR dongle!

10: SDR Application

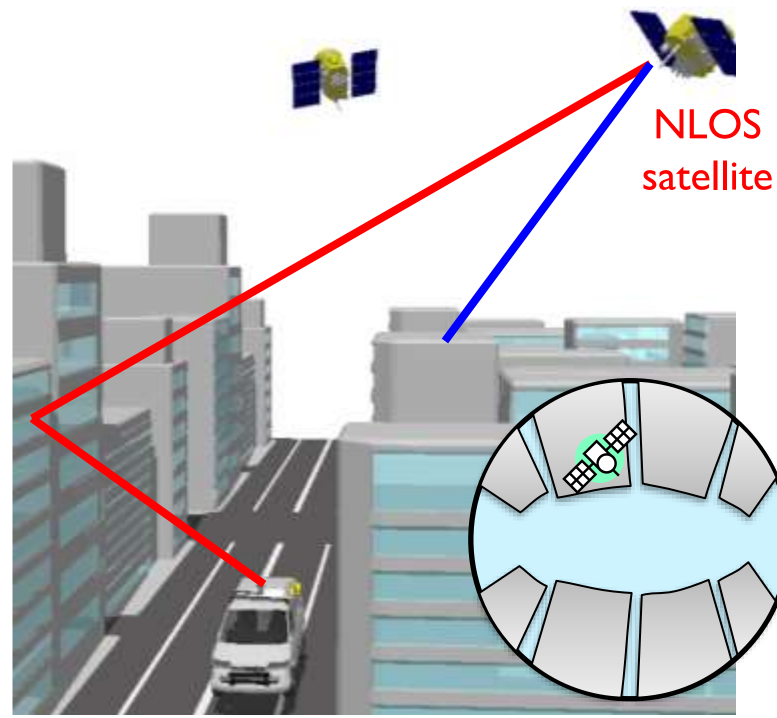
Taro Suzuki

NLOS Multipath

LOS Multipath



NLOS Multipath



LOS(Line-Of-Sight) Multipath

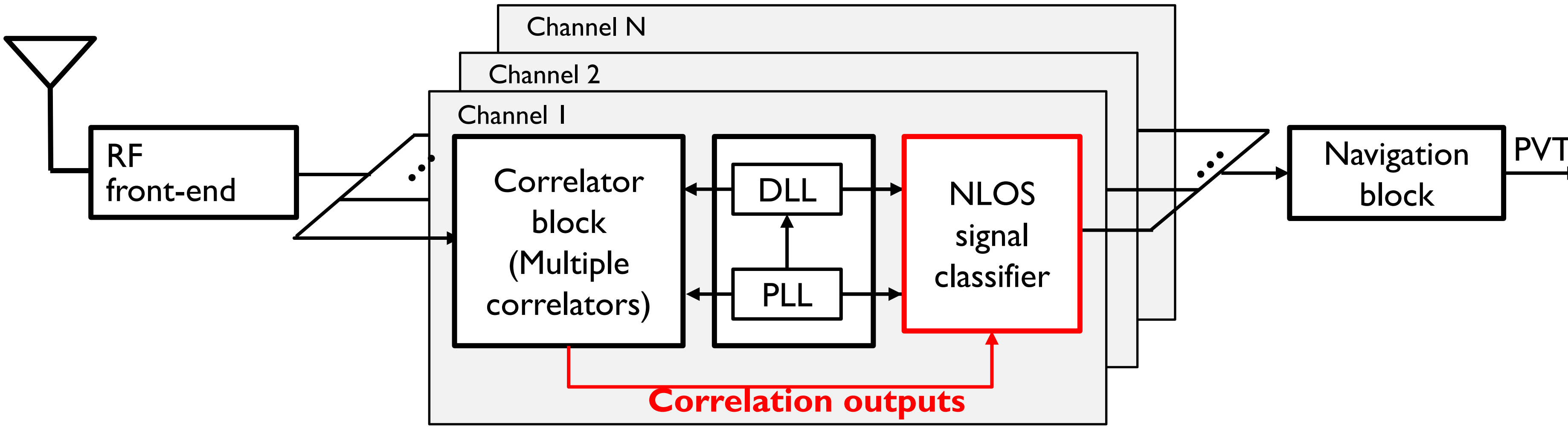
- Direct＋Reflected /Diffracted Signal
- Correlation technique is available

NLOS(Non-Line-Of-Sight) Multipath

- Only Reflected / Diffracted Signal
- Correlation technique is NOT available

NLOS Classifier

Software GNSS Receiver

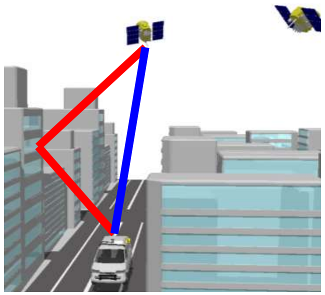


Add **NLOS signal classifier** after signal correlator block

Direct machine learning of GNSS signal correlation output, which is the most primitive GNSS signal processing output!

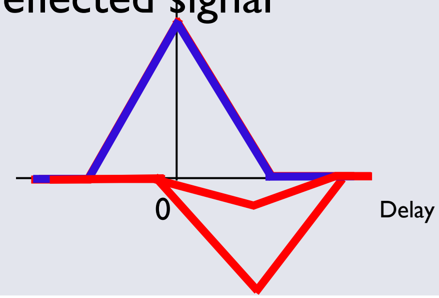
Multipath Effects for Signal Correlation

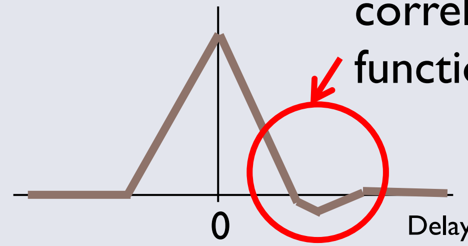
LOS Multipath



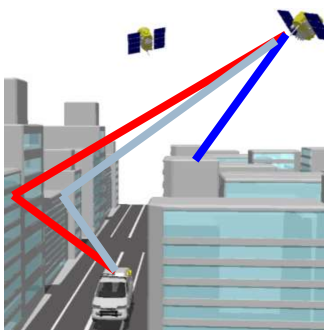
Direct and reflection/diffraction signals

- Direct signal is distorted by the reflected signal



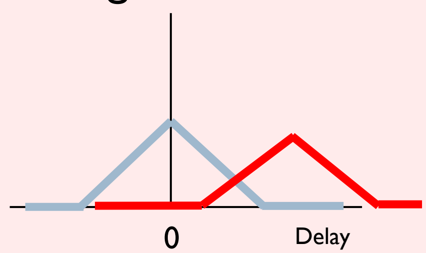


NLOS Multipath

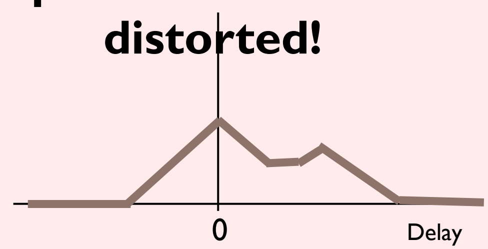


Only reflection/diffraction signals

- No direct signal
- All signals are weak



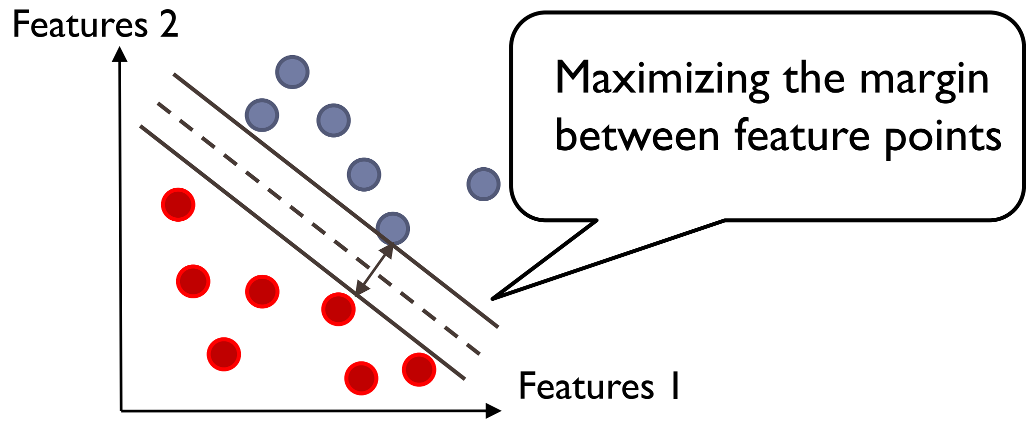
Correlation function is expected to be more distorted!



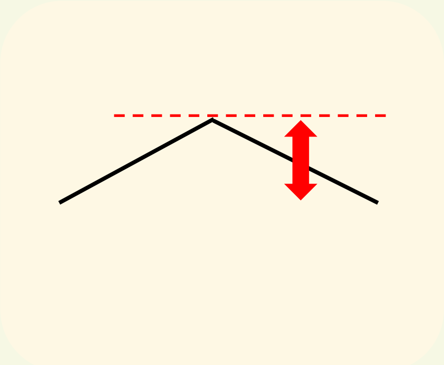
Related Research (Support Vector Machine)

Support Vector Machine

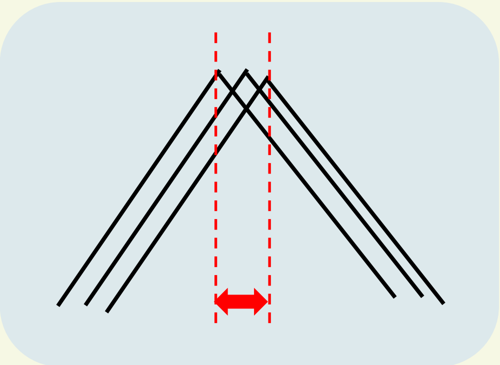
- Classification method using Supervised learning
- Maximizing the margin



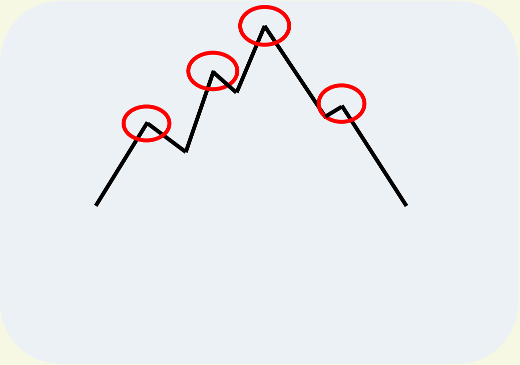
NLOS features for SVM



Signal strength vs. elevation angle

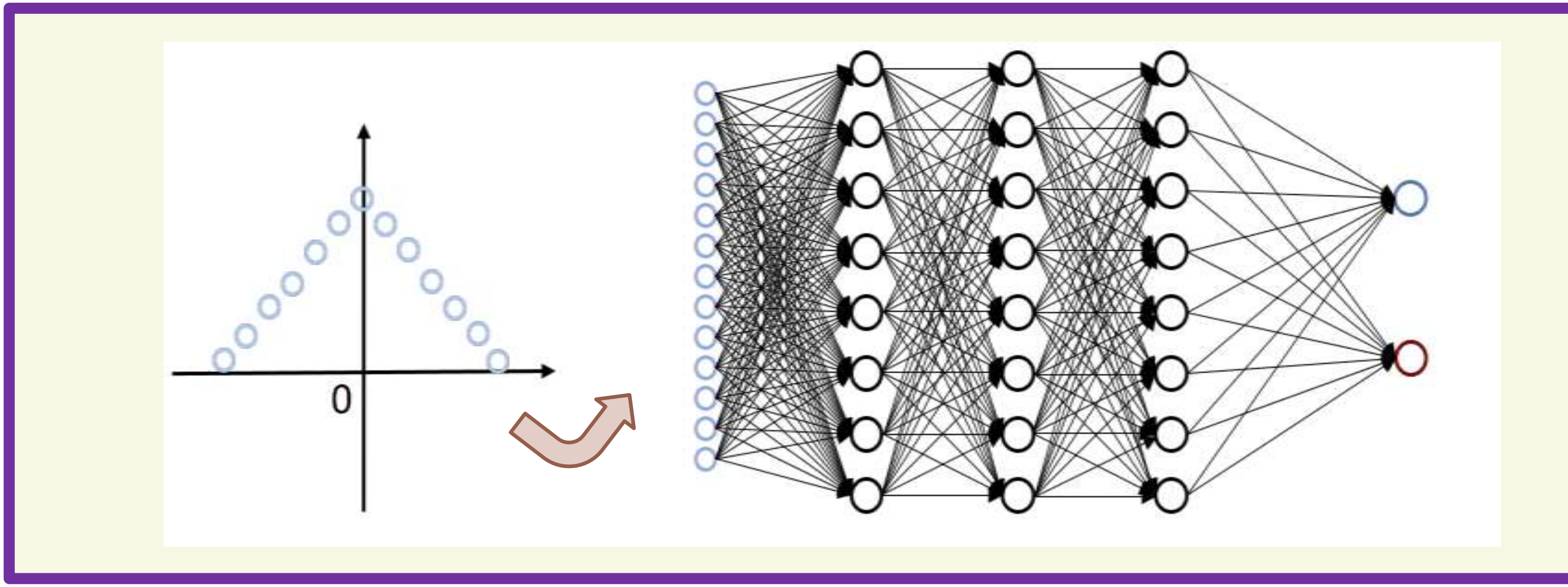


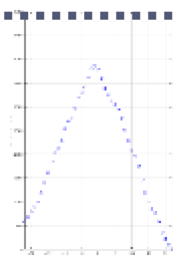
Distribution of delay of maximum correlation output



The number of local maxima

Related Research (Neural Network)

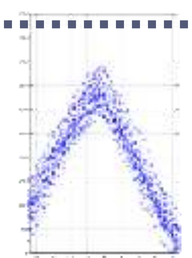




41 samples
1 ms

Correlation outputs

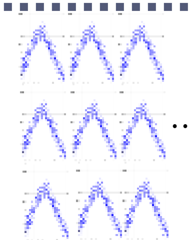
×20



820 samples
20 ms

1 unit of input data

×50,000

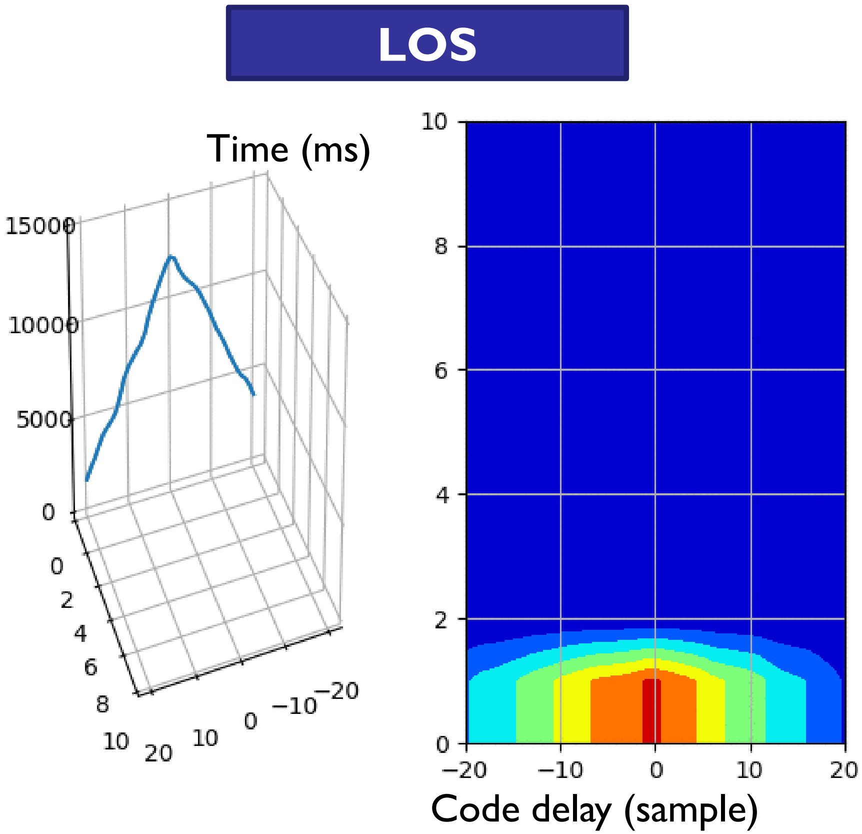


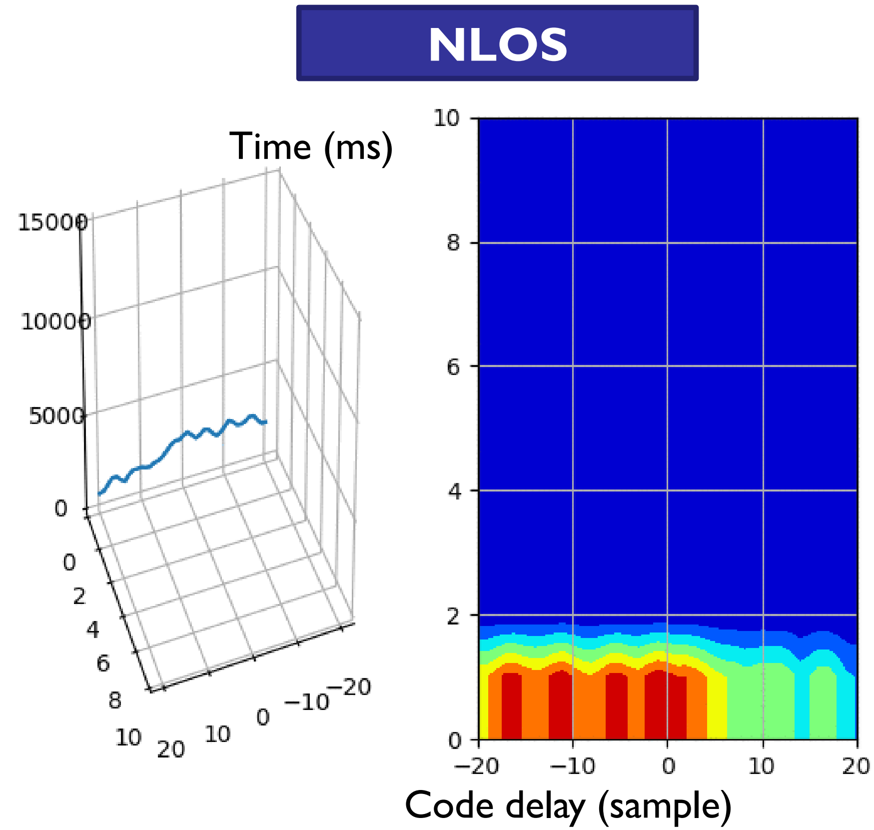
50,000 unit
Of training data

All training data of LOS

Learning LOS / NLOS correlation outputs

Idea – using Convolutional NN -



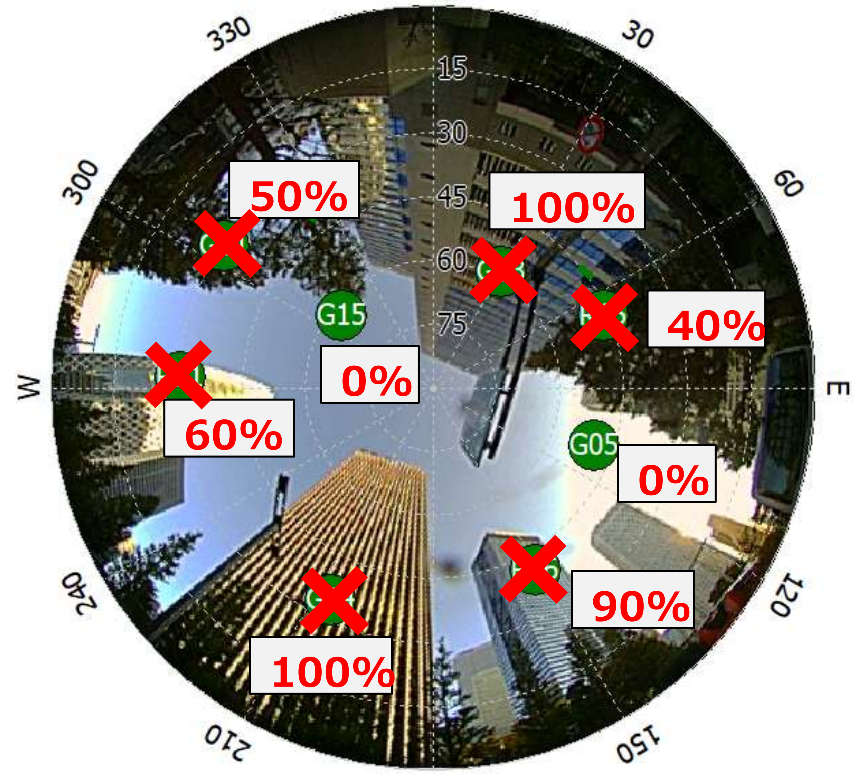


CNN can handle the **time-dependent NLOS features !**

Idea – using NLOS probability -

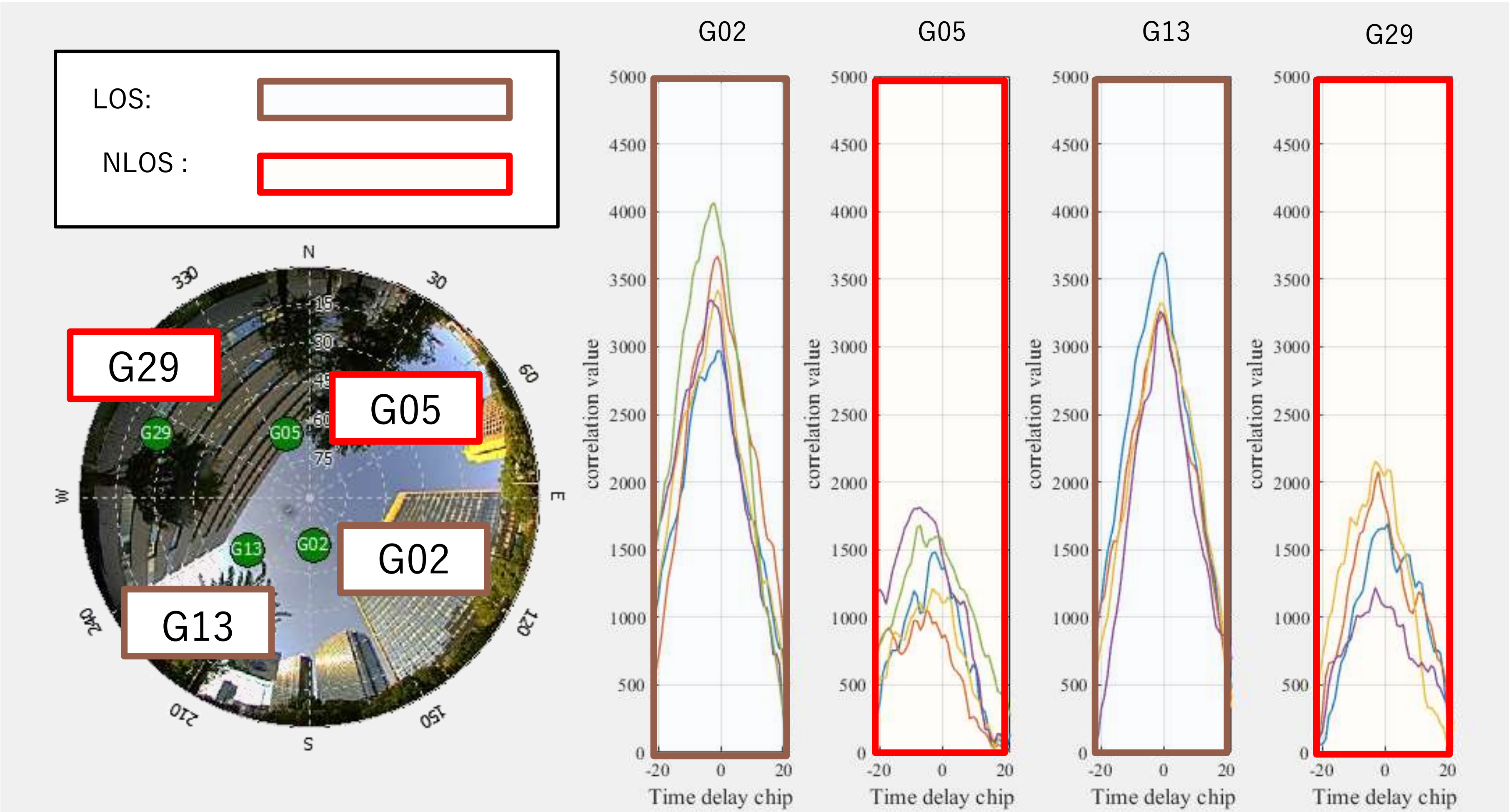
- Binary calcification of LOS/NLOS decrease positioning availability…

- Weighting pseudorange observations of GNSS using the probability of NLOS estimated by CNN



We can improve **positioning accuracy and availability !**

Correlation Outputs (GPS L1C/A)

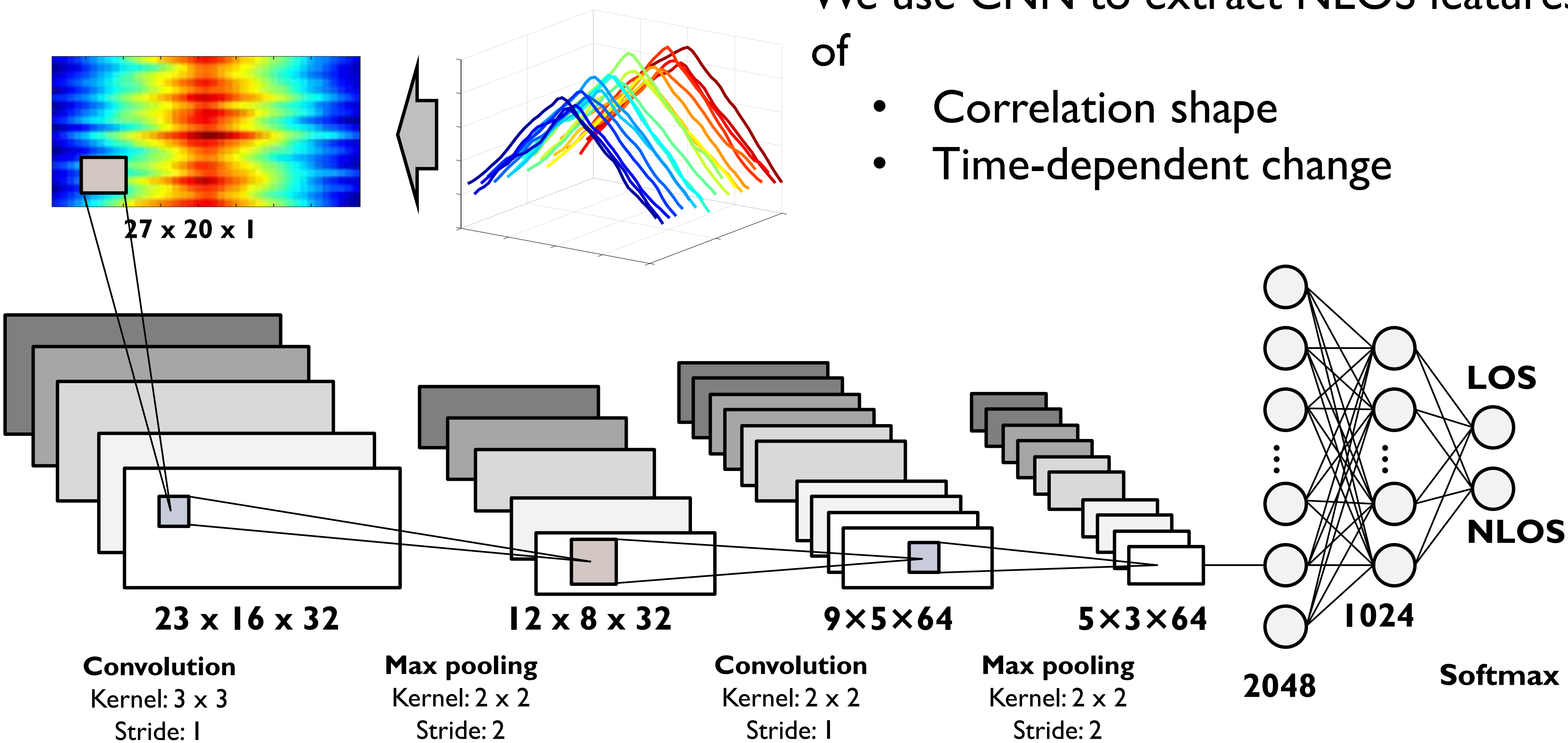


Displays 20 correlation outputs (20 ms)

Network Configuration

We use CNN to extract NLOS features of

- Correlation shape
- Time-dependent change



Weighting with NLOS probability

Pseudorange observations equation:

$$\Delta\rho = H\Delta x + \epsilon$$

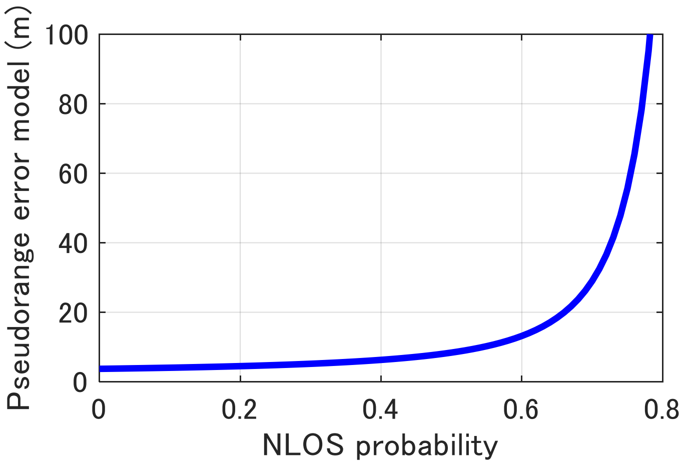
Weighted least squares method:

$$\Delta x = \left(H^T W H\right)^{-1} H^T W \Delta\rho$$

weighting matrix: $W = \begin{bmatrix} 1/\sigma_1^2 & 0 & \cdots \\ 0 & 1/\sigma_2^2 & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}$

Pseudorange error model:

$$\sigma = \beta + \exp\left(\frac{1}{(1 - p_{NLOS})}\right)$$



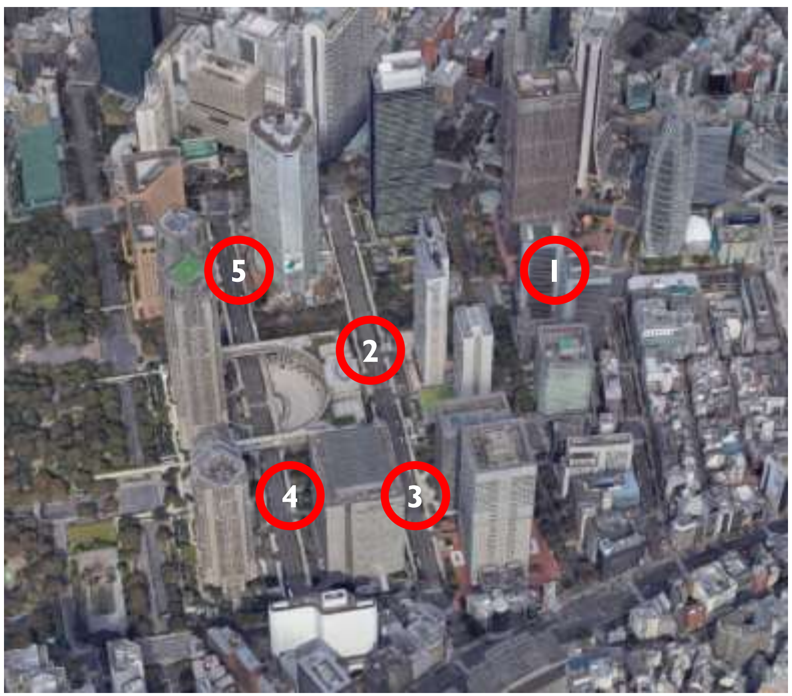
Evaluation

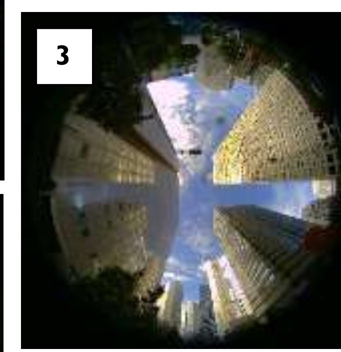
Evaluation of proposed technique in urban environment

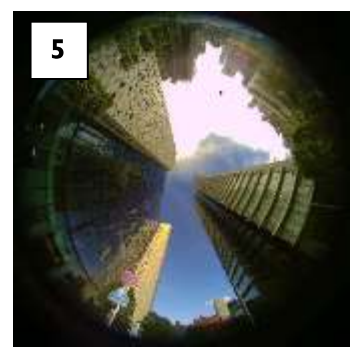
Location: Shinjuku area in Japan (5 locations)

We compare classification performance of **NN** and **CNN**

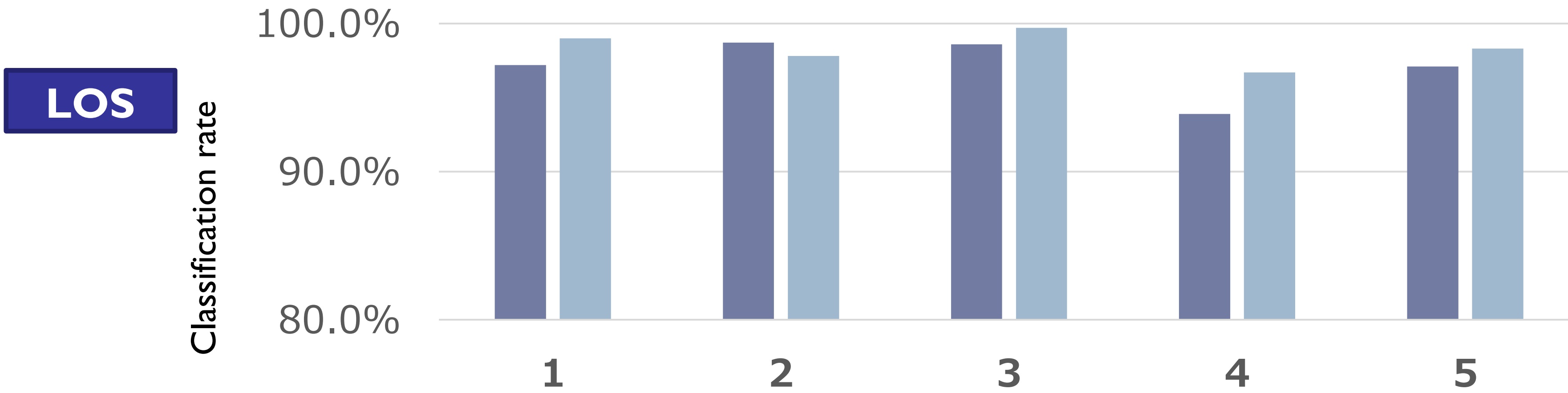
- Reference NLOS signals are manually determined from fish-eye image

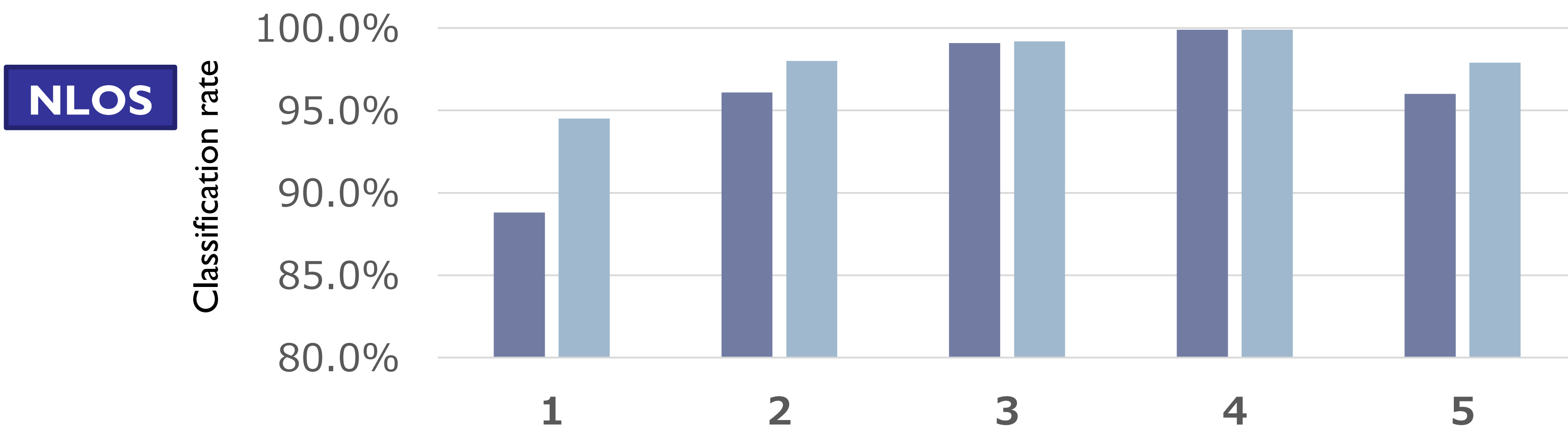






Classification Results





97.9 % NLOS signals were **correctly classified as** NLOS signals !

Positioning Test

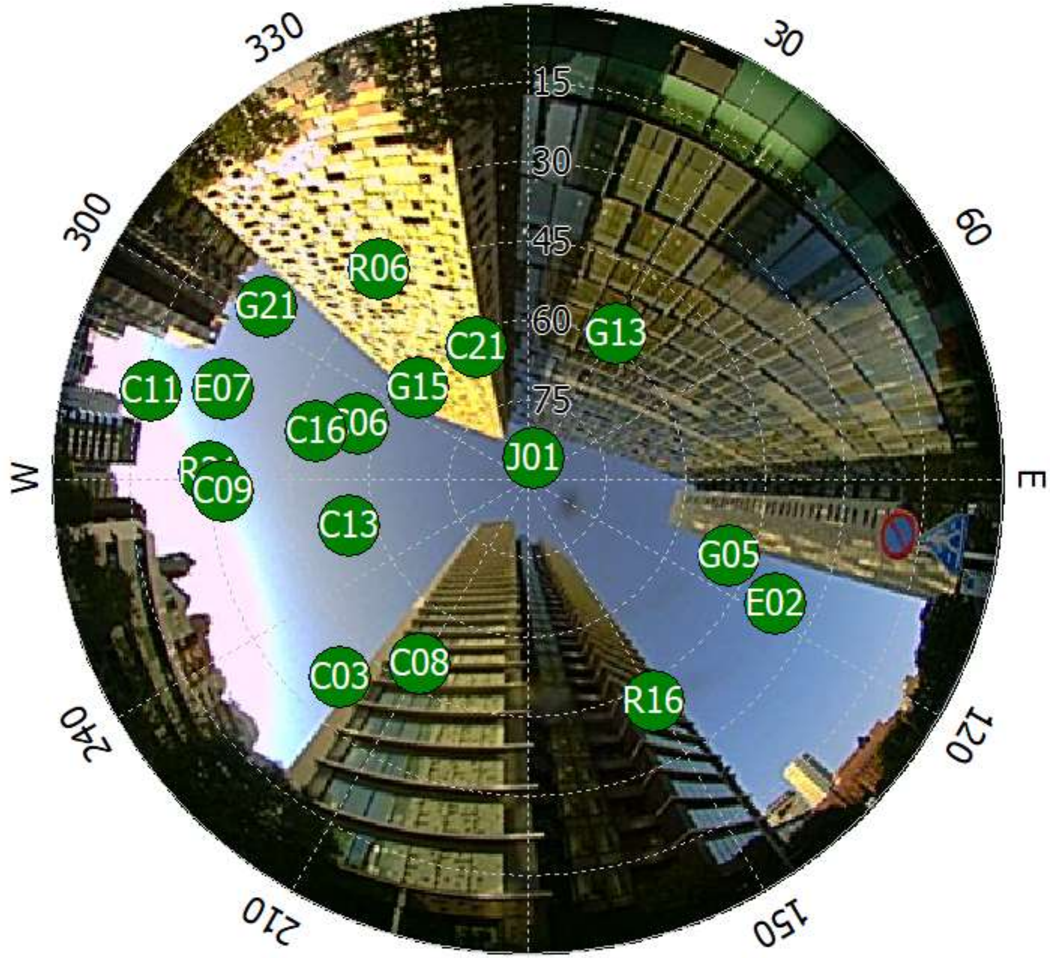
Evaluation of proposed technique in urban environment

Location: Shinjuku area in Japan

Method: Single Point Positioning (RTKLIB)

SNR mask: 35 dB-Hz, Elevation mask: 15°

Classification Result

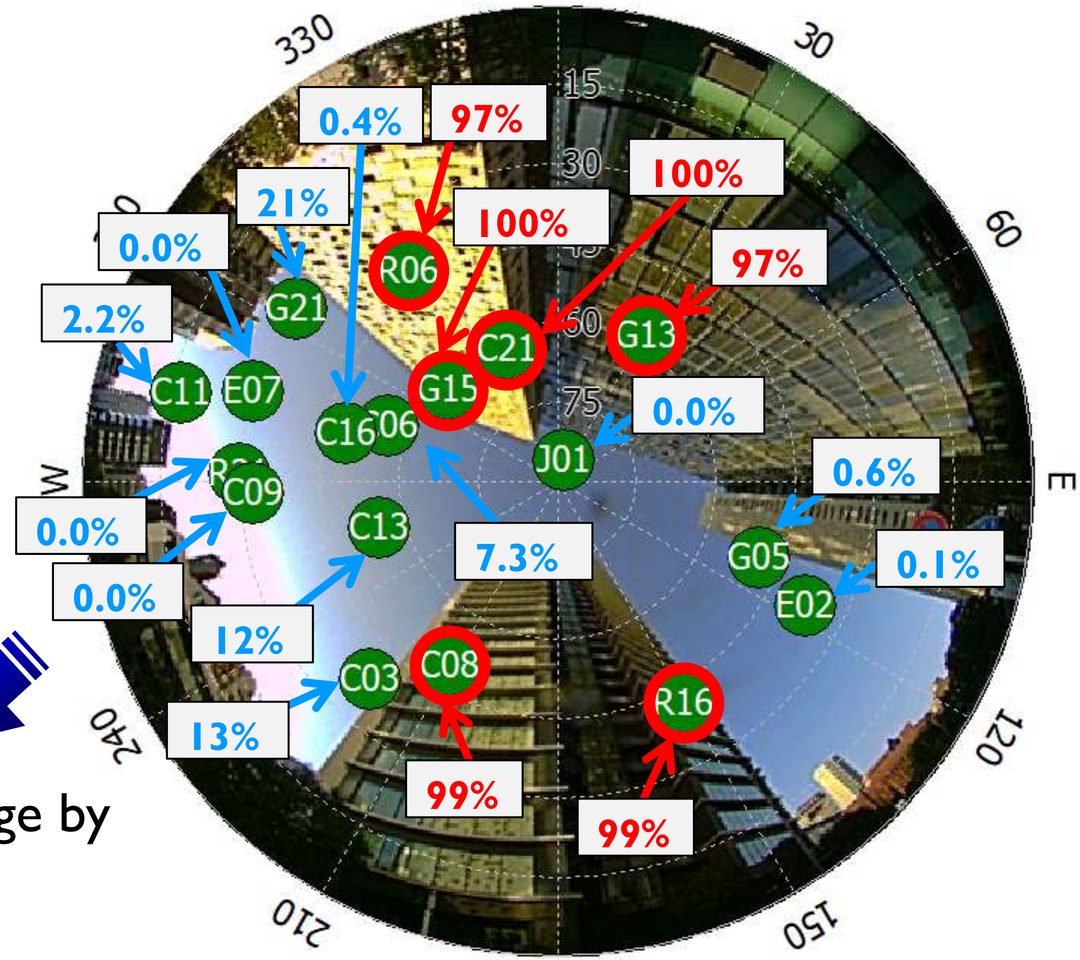


Classification Result

Satellite visibility is determined by **NLOS probability**

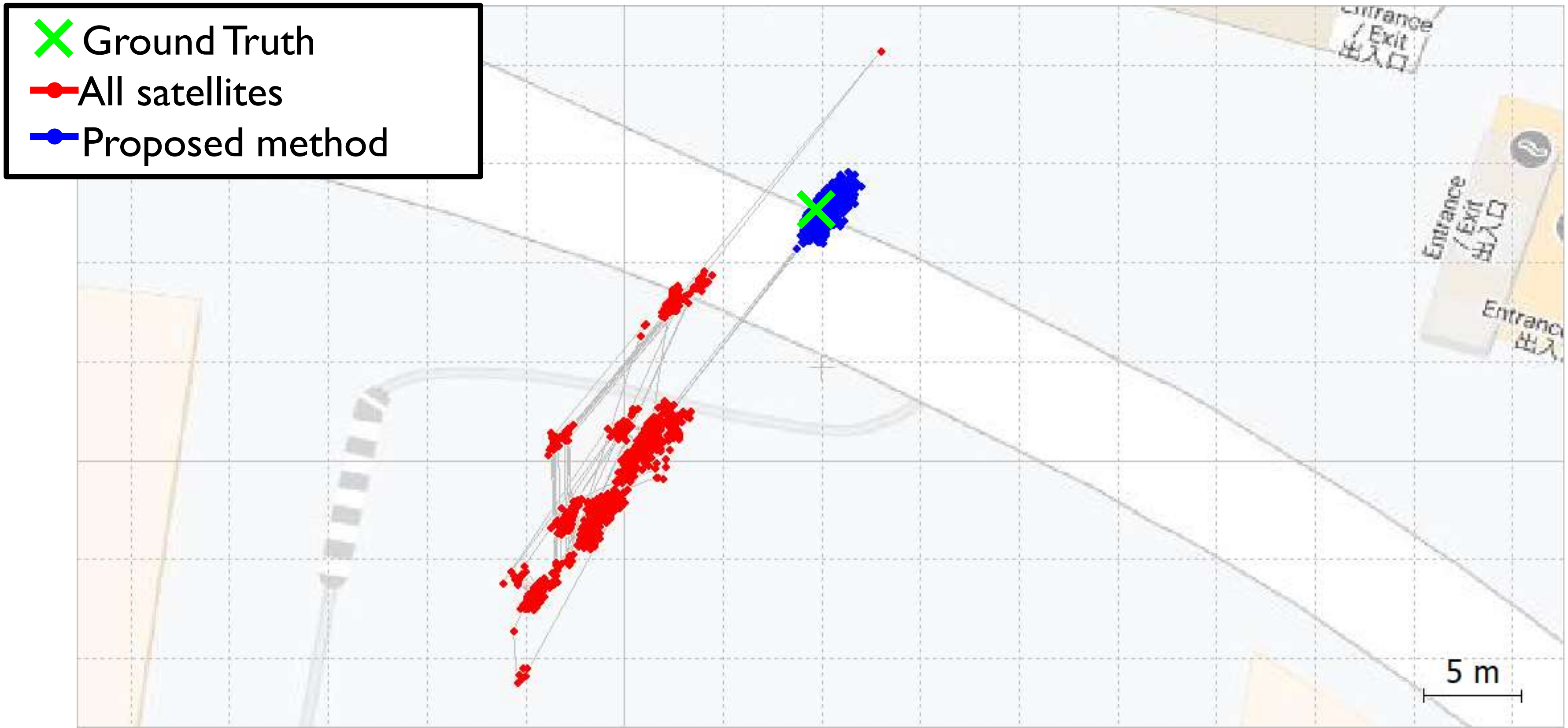
>50% NLOS

<=50% LOS



Weighting pseudorange by **NLOS probability**

Positioning Result



- Horizontal root mean square error was reduced from **34.1 m** to **1.6 m !**

Conclusion

- GNSS receiver is an aggregation of technologies from various fields
- By modifying the GNSS signal processing, a greater variety of ideas can be used than if only the normal receiver outputs were available
- The contribution of software GNSS receivers is especially important for the GNSS field, where new satellites and signals are increasing
- Software receiver technology is extremely useful for research