RF signal transmitter location by LEO satellite using TDOA and FOA method

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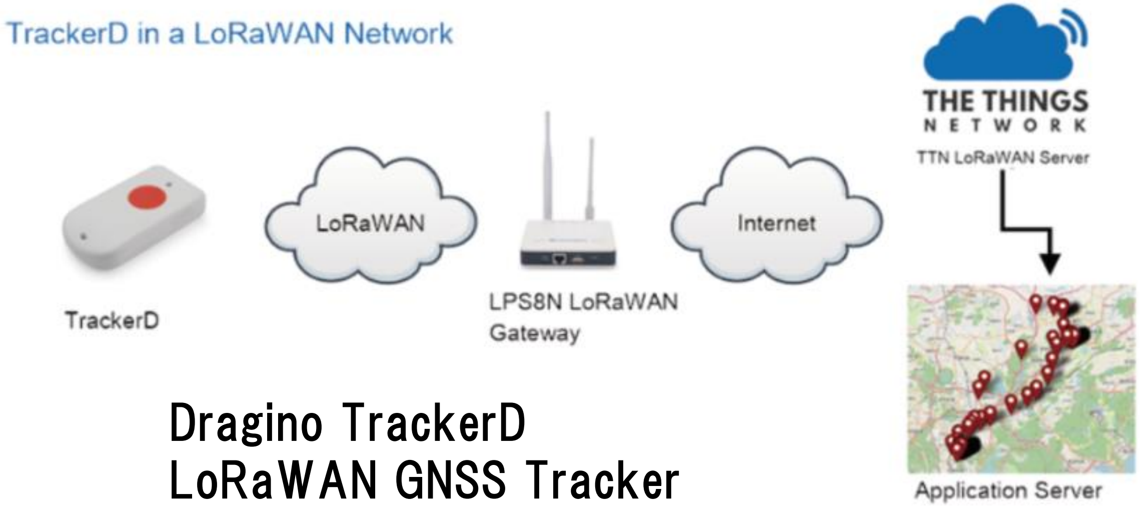
1. Demand of low power positioning

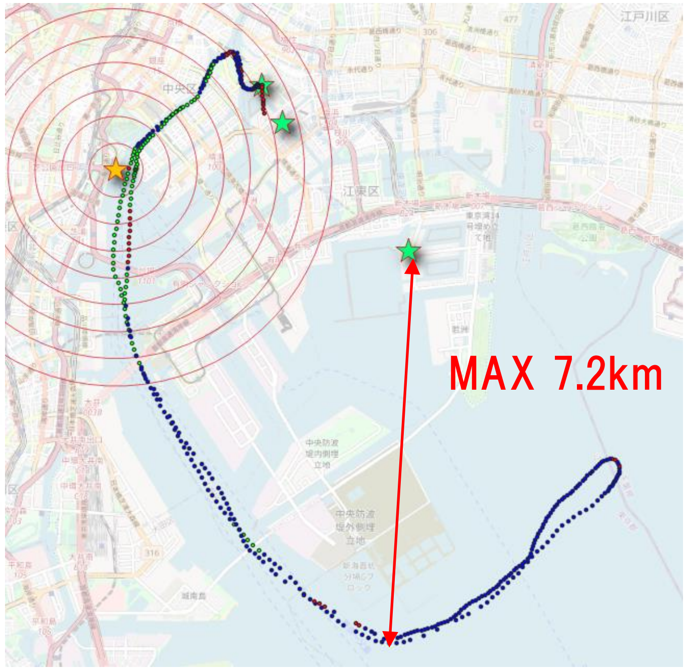
◆Now, most popular positioning method is GNSS. GNSS can provide 2~5m level accurate position in worldwide.

◆There is many LPWA (Low Power Wide Area) device which use GNSS. However, GNSS receiver's power-consumption is one of the issue.

GlobalSat LT-501H
LoRaWAN GNSS Tracker
https://www.globalsat.com.tw/en/product-273088/Compact-LoRa-GPS-Tracker-for-Personal-use-or-Asset-LT-501H-LT-501E.html



Dragino TrackerD
LoRaWAN GNSS Tracker
http://wiki.dragino.com/xwiki/bin/view/Main/User%20Manual%20for%20LoRaWAN%20End%20Nodes/TrackerD/



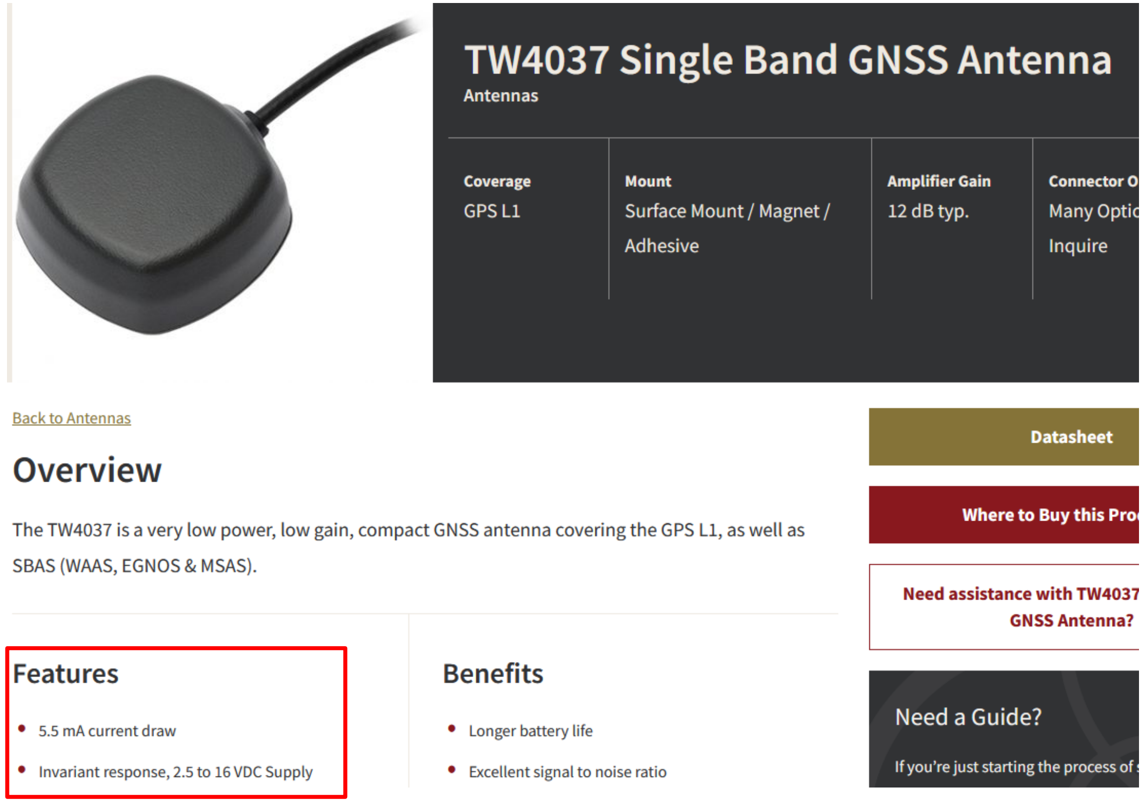
On ship experiment

1. Demand of low power positioning

◆Low power GNSS module is exist, but GNSS need active antenna with LNA (Low Noise Amplifier).

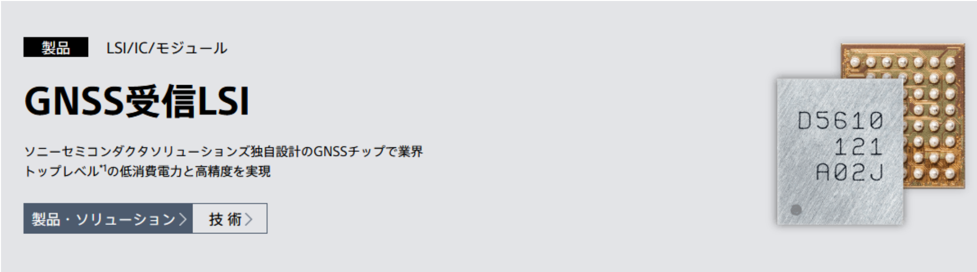
◆Low energy GNSS antenna need at least 13mW.

◆When GNSS receiver and antenna power consumption is 19mW (6+13), 1000mAh battery run out in almost 90h.



9.7 × 10.1 × 2.5 mm

u-blox MAX-M10：25mW



Sony CXD5605AGF：6mW

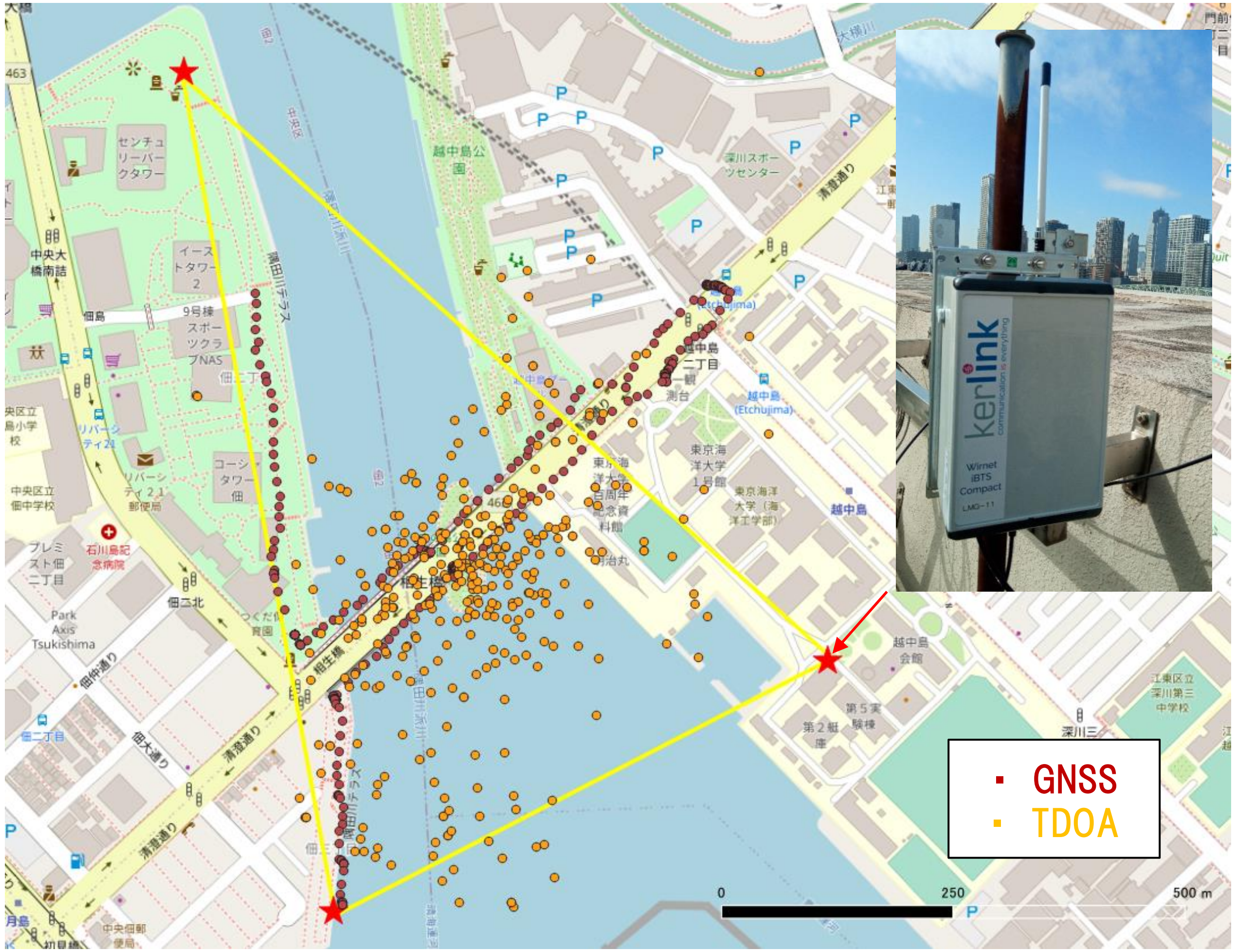
1. Demand of low power positioning

◆For LPWA device there is some application to locate device position without GNSS.

◆This test is conducted using Kerlink LoRaWAN Geolocation System.

◆In this system we installed 3 LoRaWAN gateway and LoRa device position was calculated by TDOA method.

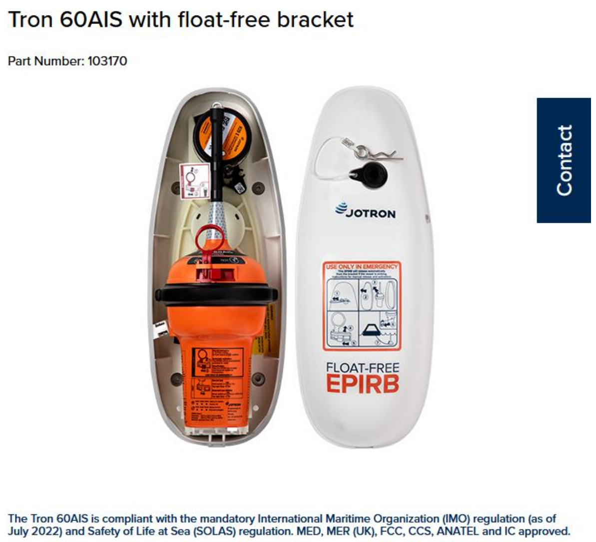
◆In this test Horizontal RMS Error by TDOA method was 130m comparing with GNSS position.

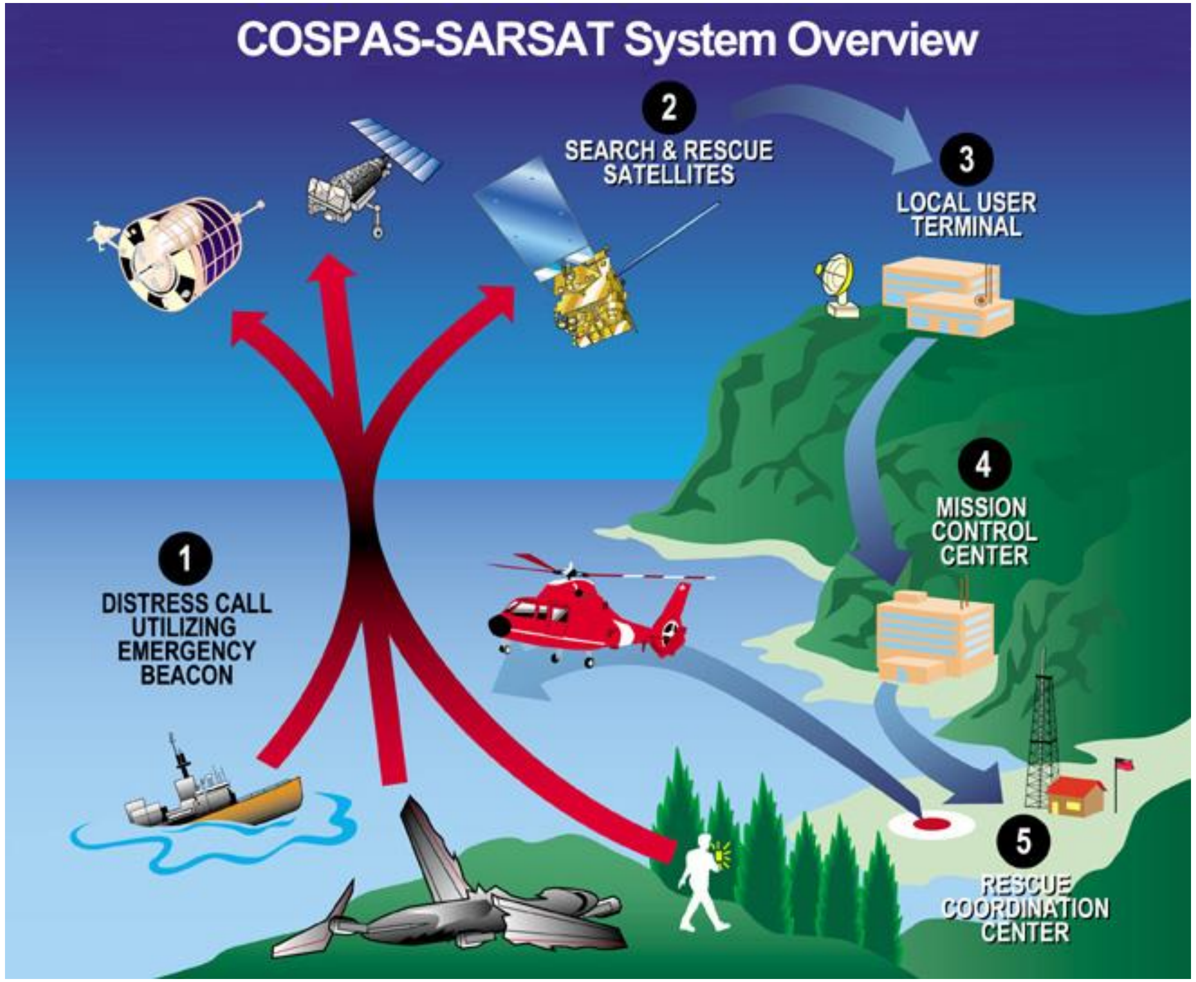


1. Demand of low power positioning

◆However, these geolocation system need to install several gateway on the field and ground obstacles provide bad effect for accuracy.

◆In SAR (Search and Rescue) field, there is location system using LEO satellite and emergency beacon.





1. Demand of low power positioning

◆LPWA signal can be received by LEO (about 500km altitude). And currently small LEO satellite developing and launching cost become cheaper.

◆Therefore, we researched about LPWA device location method using LEO.

◆COSPAS-SARSAT system use Doppler Positioning method because emergency beacon's frequency is determined.

◆However, LPWA use several channels and transmit frequency is not fixed.
Then we tried
- TDOA (Time Difference of Arrival) and
- FOA (Frequency of Arrival)
Method.

RU864/IN865/EU868/AU915/US915/KR920/AS923

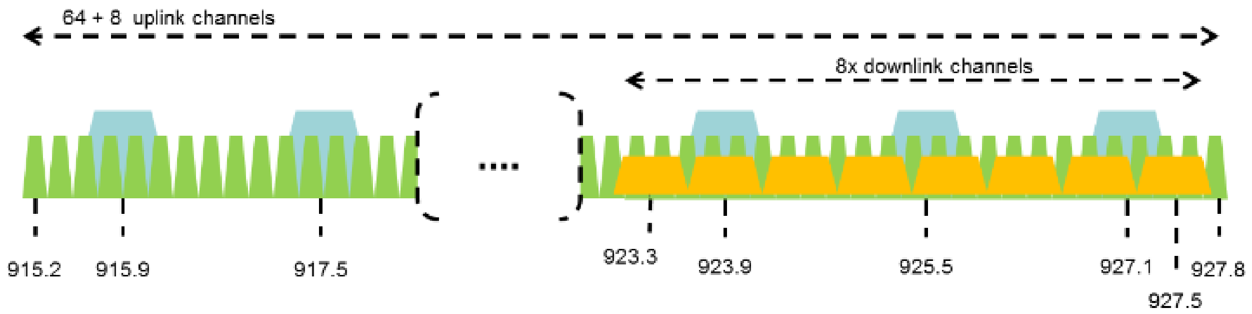


Figure 2: AU915-928 channel frequencies

2. Satellite orbit

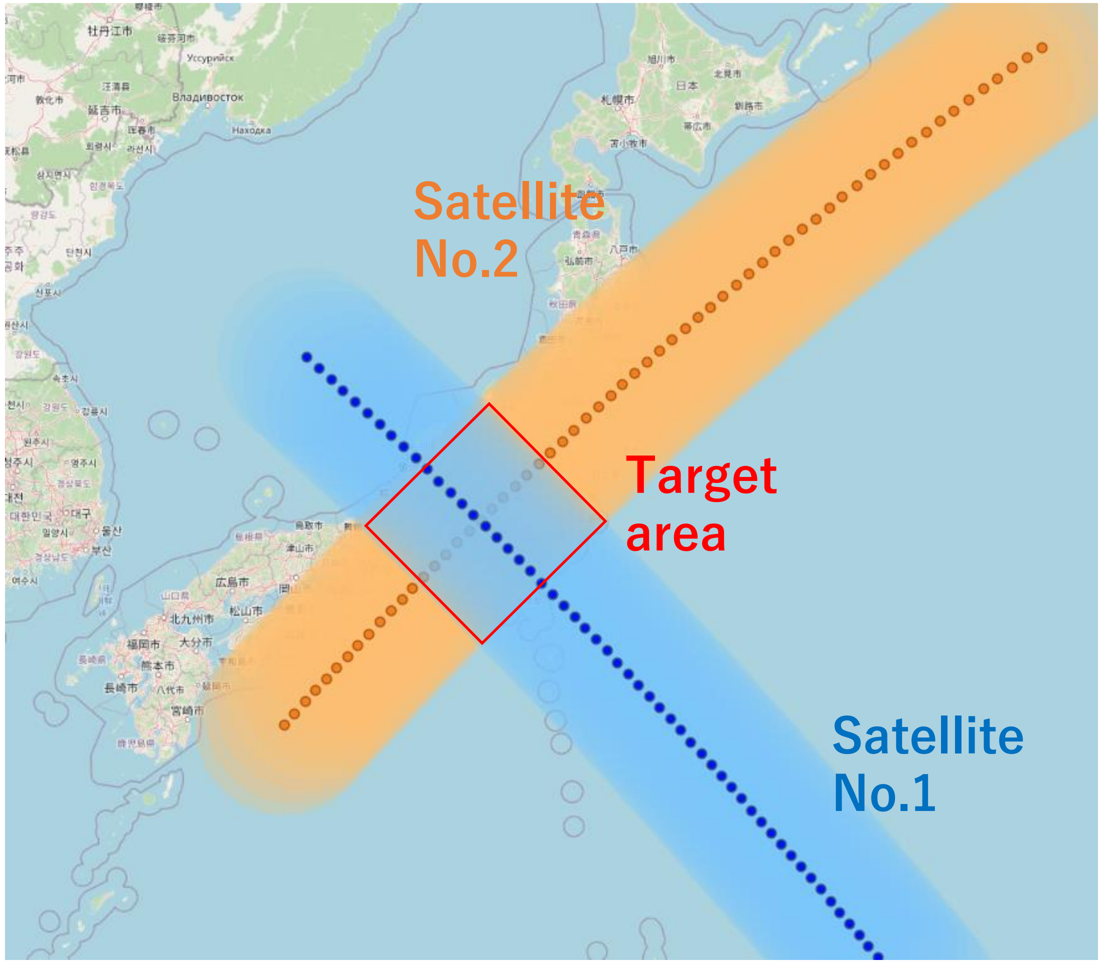
◆We simulated satellite orbit to receive LPWA signal.

◆At least two satellites are required, we used two Starlink orbit which cover Kanto Area in Japan.

◆Altitude of the satellite is 550km.

◆We calculated satellite position using SGP4 model from TLE information.

◆We assumed there is GNSS on the satellite and its position accuracy is approximately 5m.

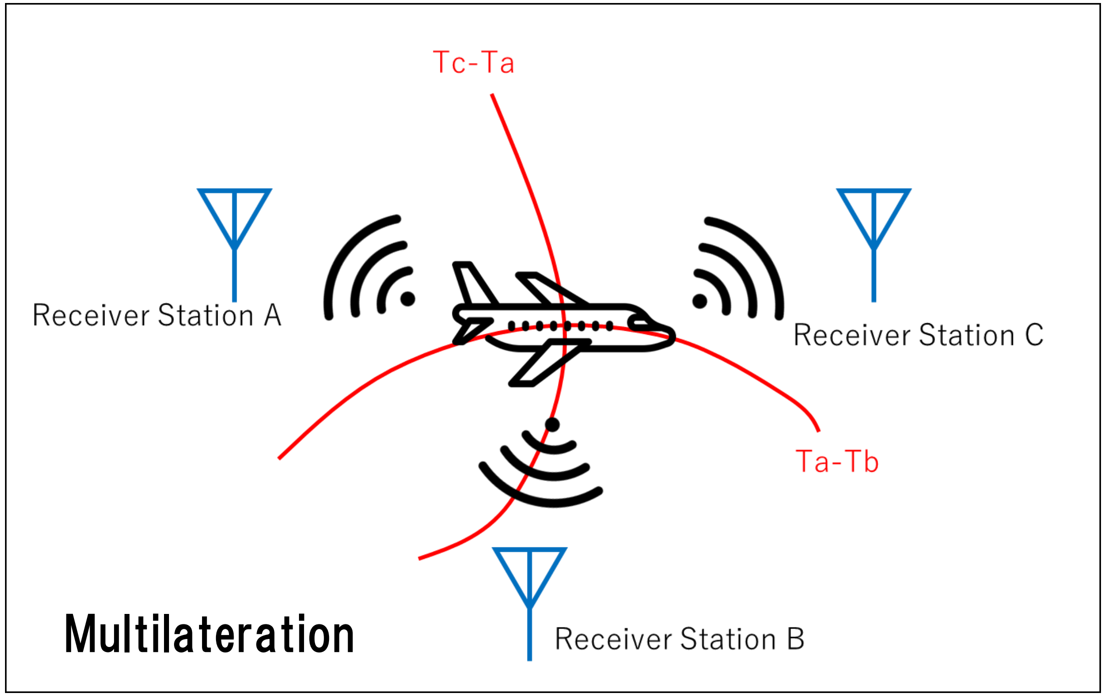


3. TDOA method

◆In TDOA method, a hyperbola is drawn from transmit signal arrival time difference between 2 stations.

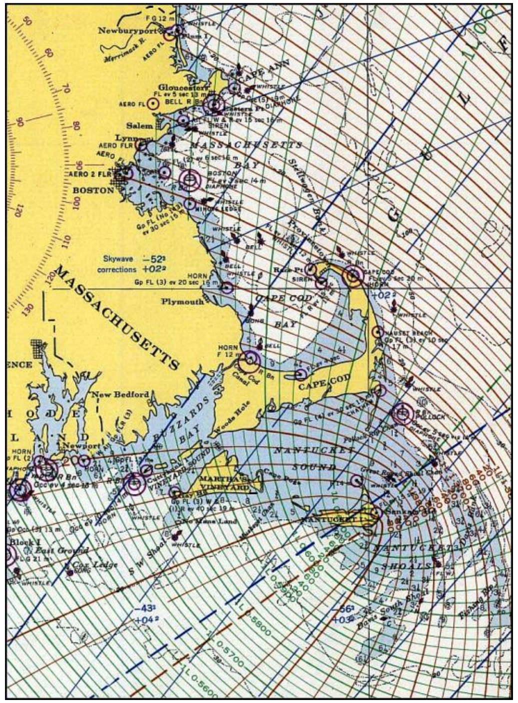
◆If there is 3 station, you can make 2 hyperbola and determine transmitter position.

◆TDOA method is used as LORAN-C and Multilateration.



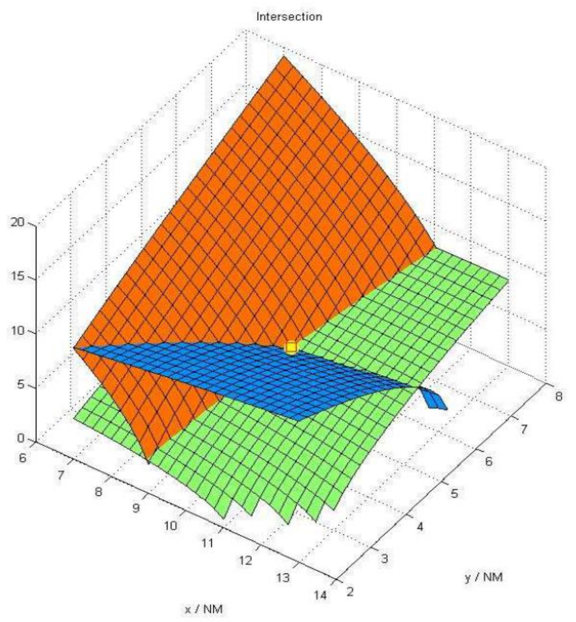
Multilateration

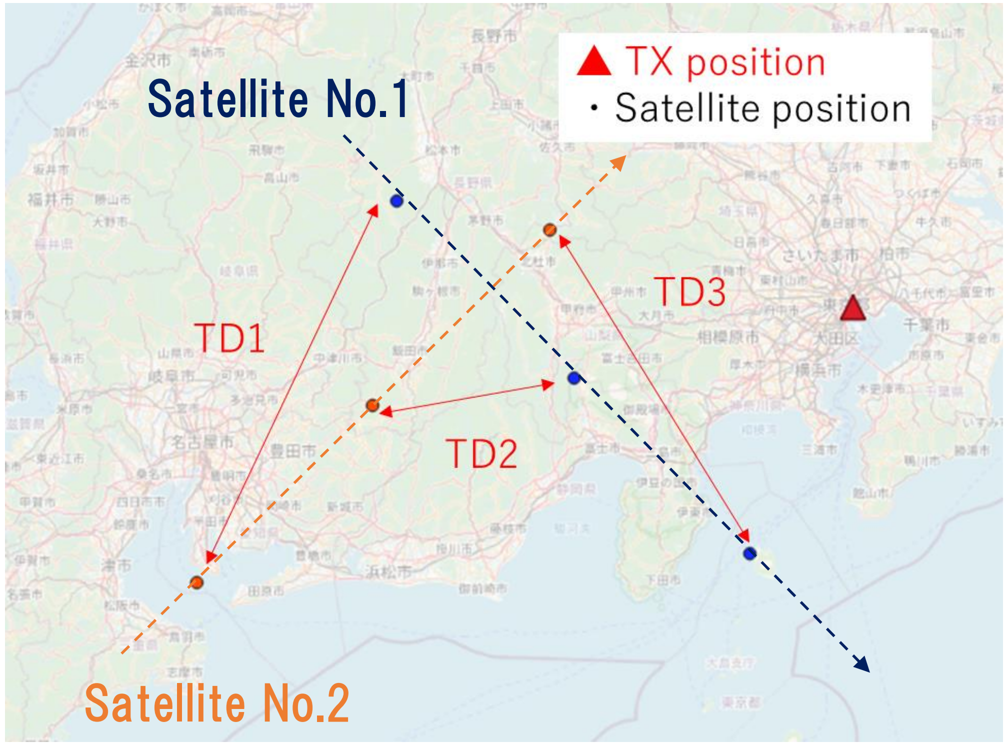
LORAN-C chart



3. TDOA method

- ◆Multilateration and LORAN-C is 2D TDOA because receivers and transmitter are in same plane. However, if we use satellite, we need to expand it to 3D TDOA.
- ◆3D TDOA needs at least 3 Time difference to make 3 hyperboloids.
- ◆To make 3 Time Difference, we simulated 3 times observation of 2 satellites.





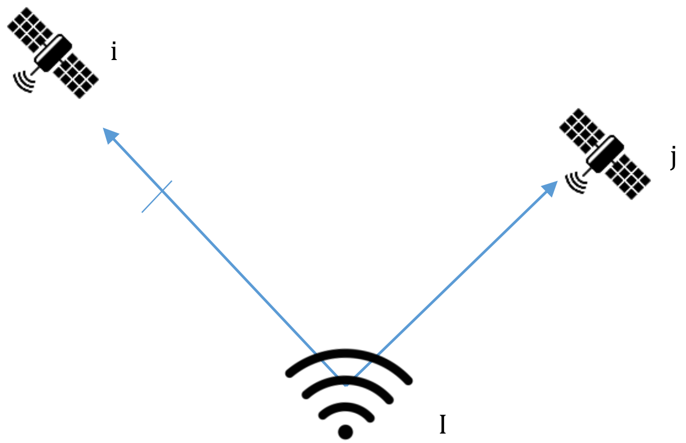
3. TDOA method

◆For 3D TDOA, we used Talory series estimation.

$$r_{ij} = \frac{d_{Ii} - d_{Ij}}{c}$$

$$= \frac{\sqrt{(x_I - x_i)^2 + (y_I - y_i)^2 + (z_I - z_i)^2} - \sqrt{(x_I - x_j)^2 + (y_I - y_j)^2 + (z_I - z_j)^2}}{c}$$

$$= r_{ij}^{x_0 y_0 z_0} + \frac{\partial r_{ij}^{x_0 y_0 z_0}}{\partial x} \Delta x + \frac{\partial r_{ij}^{x_0 y_0 z_0}}{\partial y} \Delta y + \frac{\partial r_{ij}^{x_0 y_0 z_0}}{\partial z} \Delta z$$



- *I: target*
- *i: satellite I*
- *j: satellite j*
- *d: distance*
- r_{ij}*: time difference of arrival*
- *c: speed of light*
- (x_0, y_0, z_0): *Initial Position*
- Δx, Δy, Δz*: variation from initial position to target position*

Díez-González, J.; Álvarez, R.; Sánchez-González, L.; Fernández-Robles, L.; Pérez, H.; Castejón-Limas, M. 3D Tdoa Problem Solution with Four Receiving Nodes. *Sensors* 2019, *19*, 2892. https://doi.org/10.3390/s19132892

3. TDOA method

$$\mathrm{H}\delta = Z$$

$$\begin{bmatrix} \frac{\partial r_{ij}^{x_0 y_0 z_0}}{\partial x_0} & \frac{\partial r_{ij}^{x_0 y_0 z_0}}{\partial y_0} & \frac{\partial r_{ij}^{x_0 y_0 z_0}}{\partial z_0} \\ \frac{\partial r_{kl}^{x_0 y_0 z_0}}{\partial x_0} & \frac{\partial r_{kl}^{x_0 y_0 z_0}}{\partial y_0} & \frac{\partial r_{kl}^{x_0 y_0 z_0}}{\partial z_0} \\ \frac{\partial r_{mn}^{x_0 y_0 z_0}}{\partial x_0} & \frac{\partial r_{mn}^{x_0 y_0 z_0}}{\partial y_0} & \frac{\partial r_{mn}^{x_0 y_0 z_0}}{\partial z_0} \end{bmatrix} \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = \begin{bmatrix} r_{ij} - r_{ij}^{x_0 y_0 z_0} \\ r_{kl} - r_{kl}^{x_0 y_0 z_0} \\ r_{mn} - r_{mn}^{x_0 y_0 z_0} \end{bmatrix}$$

$$\delta = [H^T Q^{-1} H]^{-1} \quad H^T Q^{-1} \mathrm{Z}$$

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix}$$

- Q: Covariance matrix of estimation error

$$\begin{bmatrix} 1,0,0 \\ 0,1,0 \\ 0,0,1 \end{bmatrix}$$

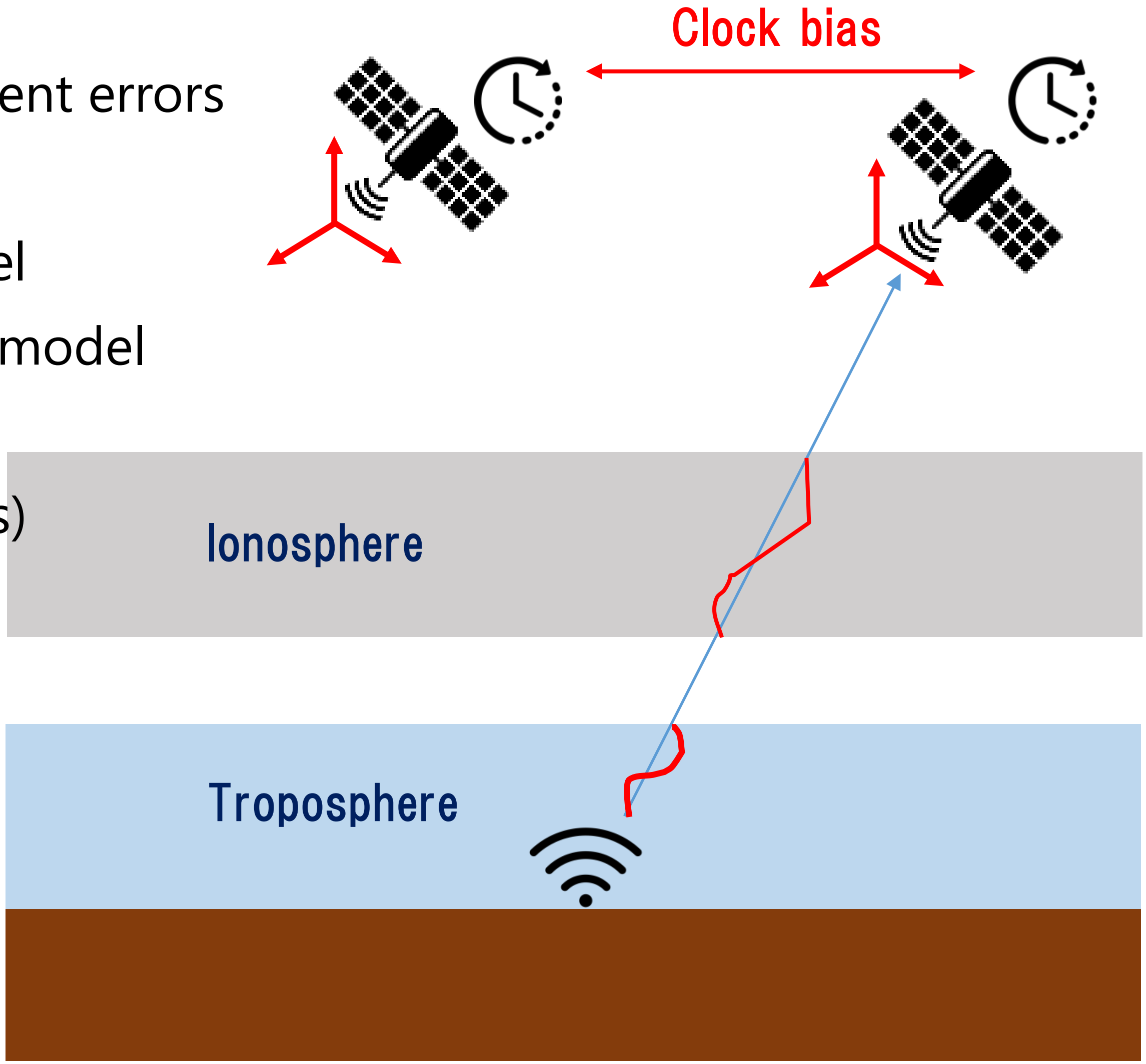
- Loop until $\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \approx 0$

4. Evaluation of TDOA

◆From satellite's observation point and transmitter point, we simulated transit time and then make Time Differences.

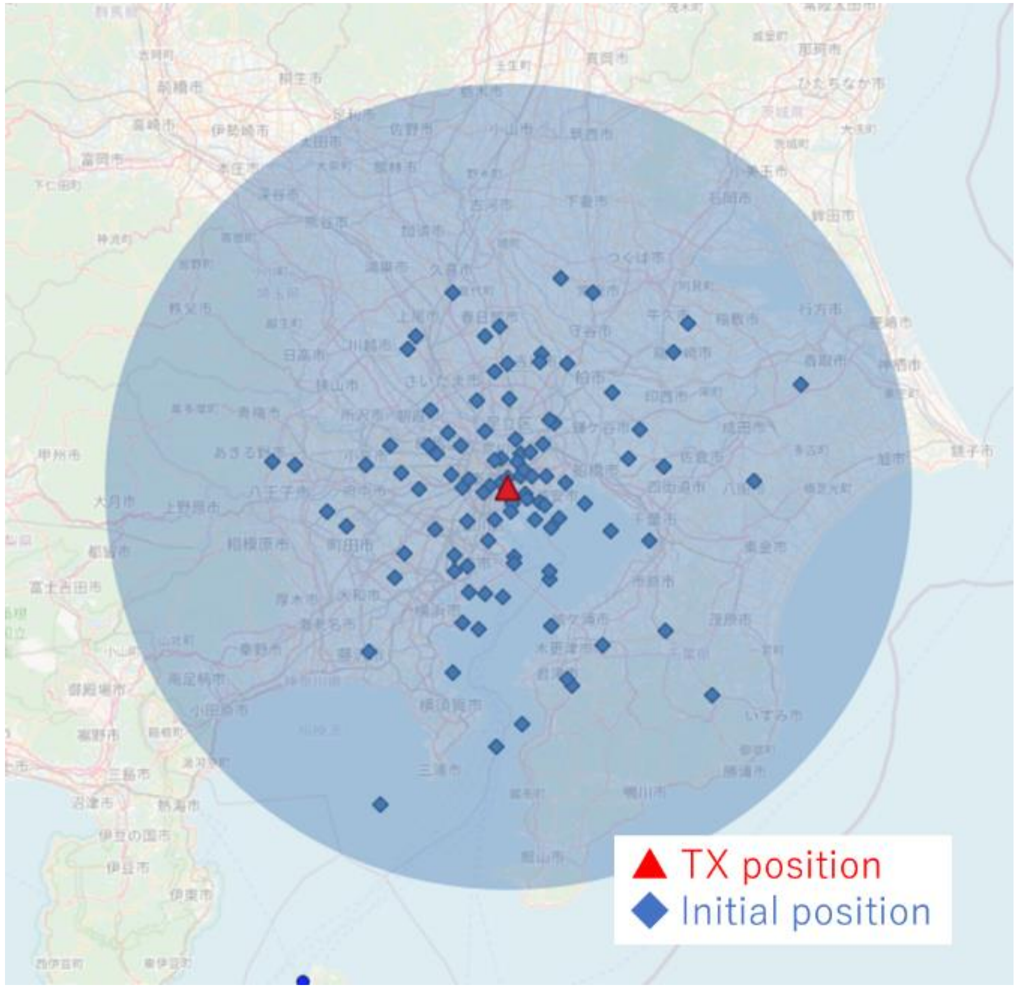
◆This transit time include following measurement errors

- 5 m satellite position error
- Ionospheric delay using the Klobuchar model
- Tropospheric delay using the Saastamoinen model
- Receiver clock bias (mean=0, σ=40ns)
- Signal receiving time error (mean=0, σ=60ns)



4. Evaluation of TDOA

- ◆Initial position was given from random point inside 100km distance from Tx point
- ◆100 times simulation was conducted.



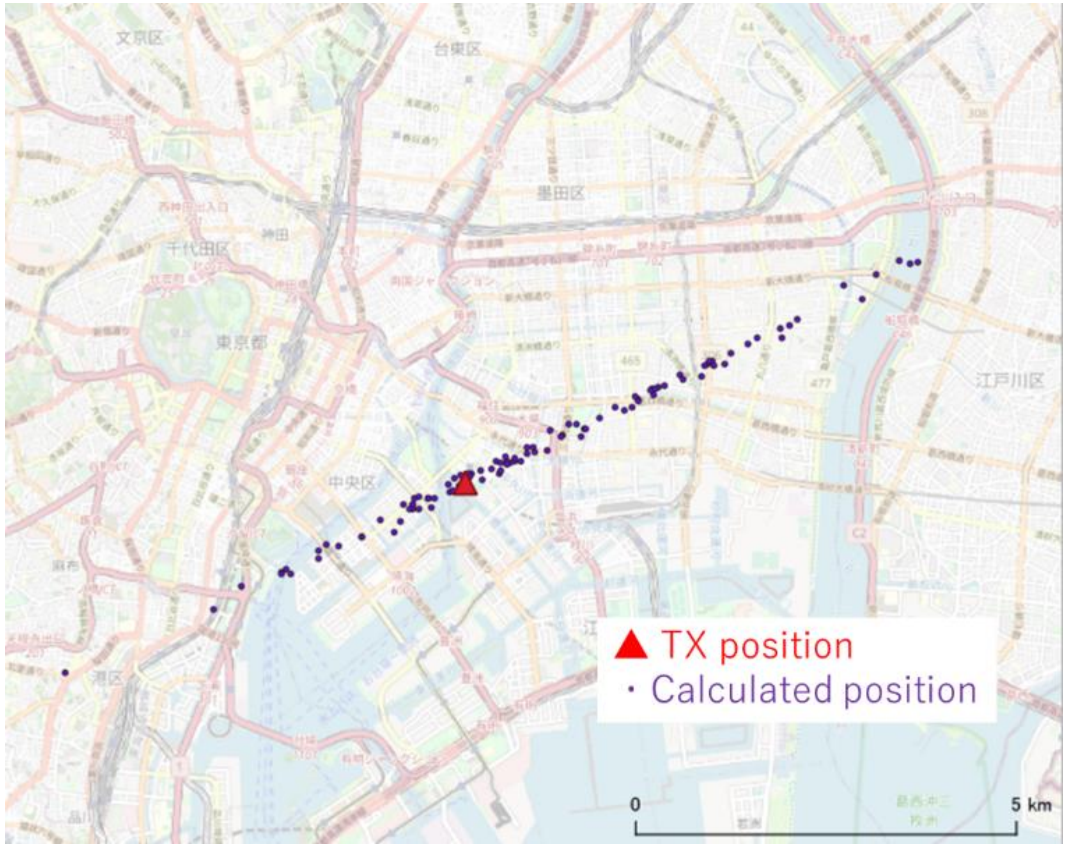
4. Evaluation of TDOA

◆We simulated 3 observation interval.

◆If observation interval is short, positioning accuracy will decline.

◆When observation interval is 15 sec,
horizontal RMS error is 2.5km

	5 sec interval		10 sec interval		15 sec interval	
	2D error	3D error	2D error	3D error	2D error	3D error
AVG[m]	13440	44762	3403	11716	1942	6764
STD[m]	12592	41534	2856	9833	1608	5612
RMS[m]	18417	61063	4443	15296	2522	8789



Horizontal Plot of 15 sec interval

5. FOA method

◆FOA need at least two satellites and several times observation of Frequency of Arrival.

◆FOA can calculate transmitter position without knowing its frequency.

◆FOA and position, velocity of satellite are required.

◆$\boldsymbol{x}$ was obtained by weighted least-squares method.

$$z(t_k) = h(t_k) + v(t_k)$$

$$h(t_k) = f_c + \frac{1}{\lambda} \frac{\left(\mathbf{v}_U(t_k)\right)^T \left(\mathbf{p}_T - \mathbf{p}_U(t_k)\right)}{\|\mathbf{p}_T - \mathbf{p}_U(t_k)\|}$$

$$\boldsymbol{x} \doteq \begin{pmatrix} \mathbf{p}_T \\ f_c \end{pmatrix}$$

k : Observation number (0~n)
$z(t_k)$ ：Measured FOA（Frequency Of Arrival）
$h(t_k)$ ：True FOA
$v(t_k)$ ：Measurement error by thermal noise
f_c ：Transmit frequency
λ ：Length of wave (=c/fc)
$\mathbf{p}_T$ ：xyz position of transmitter
$\mathbf{p}_U(t_k)$ ：xyz position of satellite
$\mathbf{v}_U(t_k)$ ：xyz velocity of satellite

Takeshi Amishima. Theoretical FOA Based Geolocation Accuracy by Single Moving Platform Considering Orbital Error. IEICE Transactions on Communications, Vol.J106-B, No.2, pp.88-100, 2023

6. Evaluation of FOA

◆We used same satellite orbit , time and transmitter position which were used in TDOA evaluation.

◆5 times observation with 10 sec interval.

◆FOA was simulated from satellite position, velocity, and transmitter position.

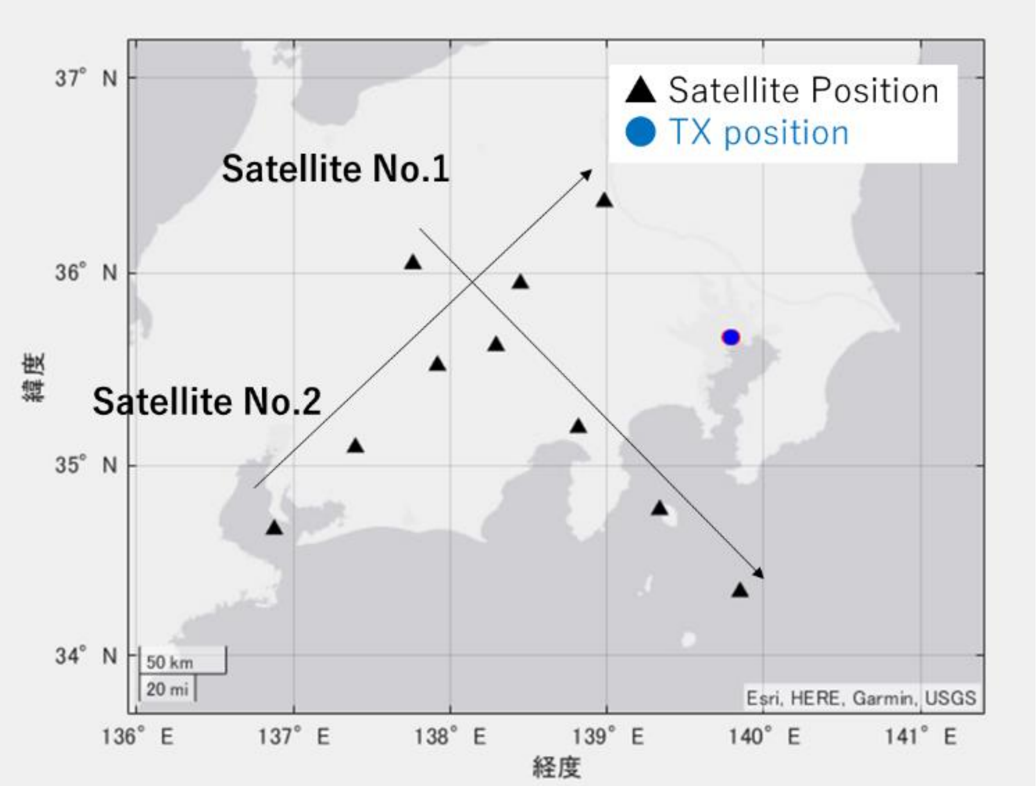
◆Added measurement error is

- 10m satellite position error
- Satellite velocity error (mean=0, σ=0.1m/s)
- Thermal noise (mean=0, σ=2Hz/10Hz/50Hz)

◆FOA accuracy depend on the transmitter signal frequency, and we evaluated 2 patterns of 1GHz and 5GHz.

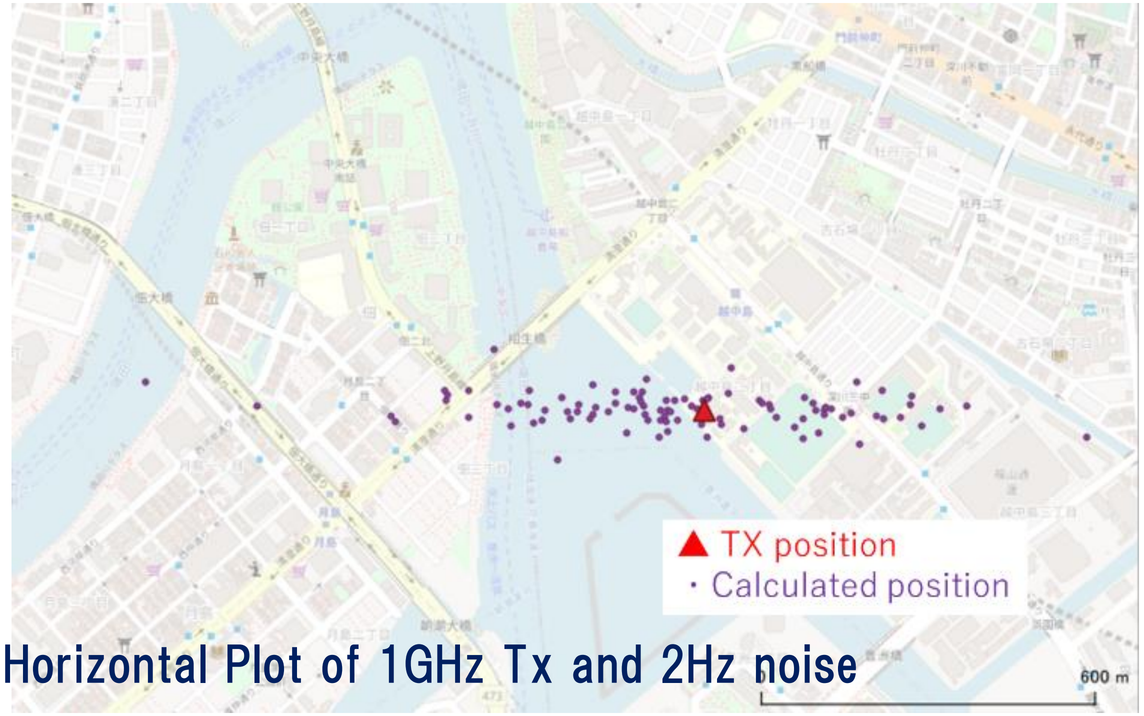
◆Initial Tx point was 20km away from true transmitter position.

◆100 times simulation was conducted.



6. Evaluation of FOA

- ◆We calculated positioning accuracy of 6 pattern.
- ◆The higher the frequency of the transmitter signal, the higher the accuracy.
- ◆The higher the thermal noise, the lower the accuracy.
- ◆When thermal noise is 2Hz, horizontal RMS error was 300m in 1GHz.



Horizontal Plot of 1GHz Tx and 2Hz noise

1 GHz				5 GHz			
FOA thermal noise	2D RMS Error[m]	3D RMS Error[m]	Frequency Estimation Error[Hz]	FOA thermal noise	2D RMS Error[m]	3D RMS Error[m]	Frequency Estimation Error[Hz]
2 Hz	292	324	8.7	2 Hz	117	131	17.8
10 Hz	1652	1833	49.2	10 Hz	331	364	49.4
50 Hz	7820	8941	238.1	50 Hz	1828	2018	277.9

7. Conclusion

◆We simulated two different methods to location LPWA device from LEO satellite.

◆We focused on the positioning methods that available when we don’t know transmitter signal frequency.

◆TDOA accuracy was several km level and FOA accuracy was few hundreds meter level in the best case.

◆TDOA needs accurate clock module.

◆FOA needs fine FFT’s frequency resolution and low noise.

Future Work

◆When we combined two methods, the accuracy will be improved.

◆Measure real timing error and frequency noise by SDR.

◆Estimate positioning error ellipsoid.

◆Simulate good satellite orbit which can cover wide area for long time.