Tsunami data assimilation and forecast in the Kii Channel using high-frequency radar: Bathymetry effects on the propagation of measurement error

紀伊水道における海洋レーダーを用いた津波データ同化・予測：海底地形が観測誤差の伝播に及ぼす影響

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背景：津波のモニタリング・検知・予測における海洋レーダーの役割

海洋レーダーは津波高を直接測るのではなく、**海面流速**を観測する。1台で視線方向流速、2台以上で東西・南北の水平流速を算出できる。

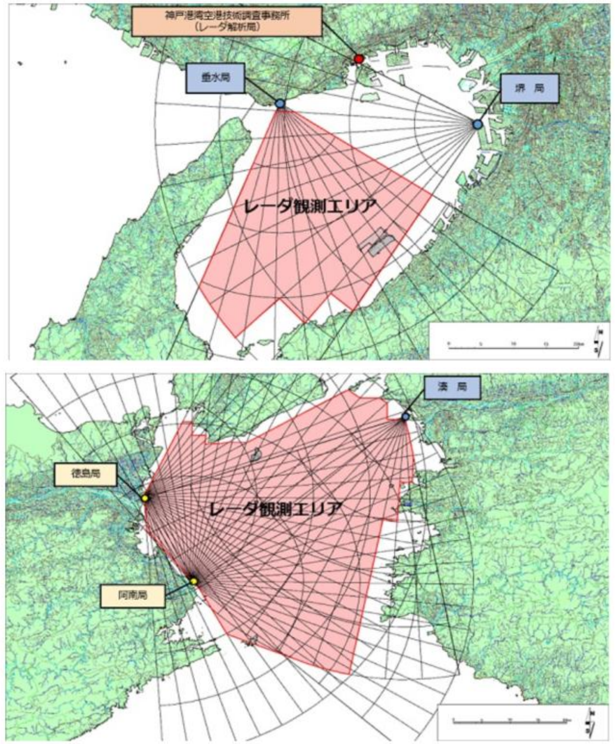
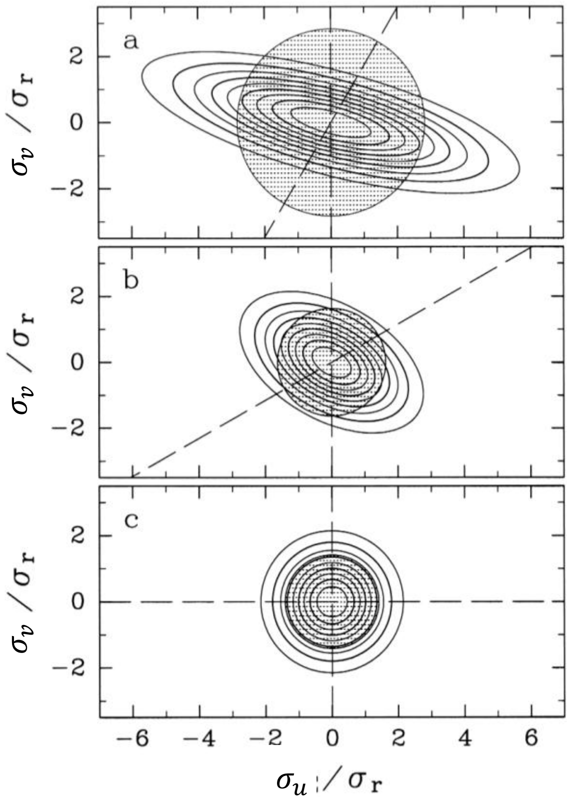
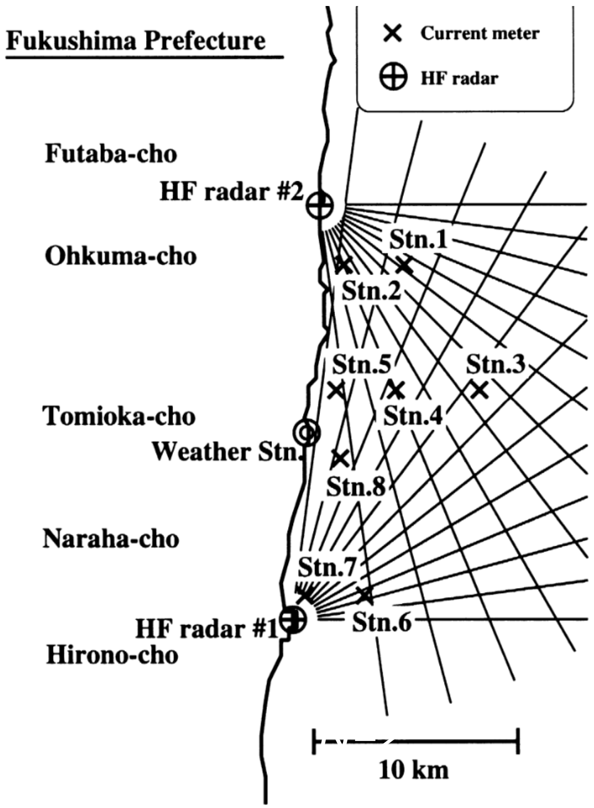


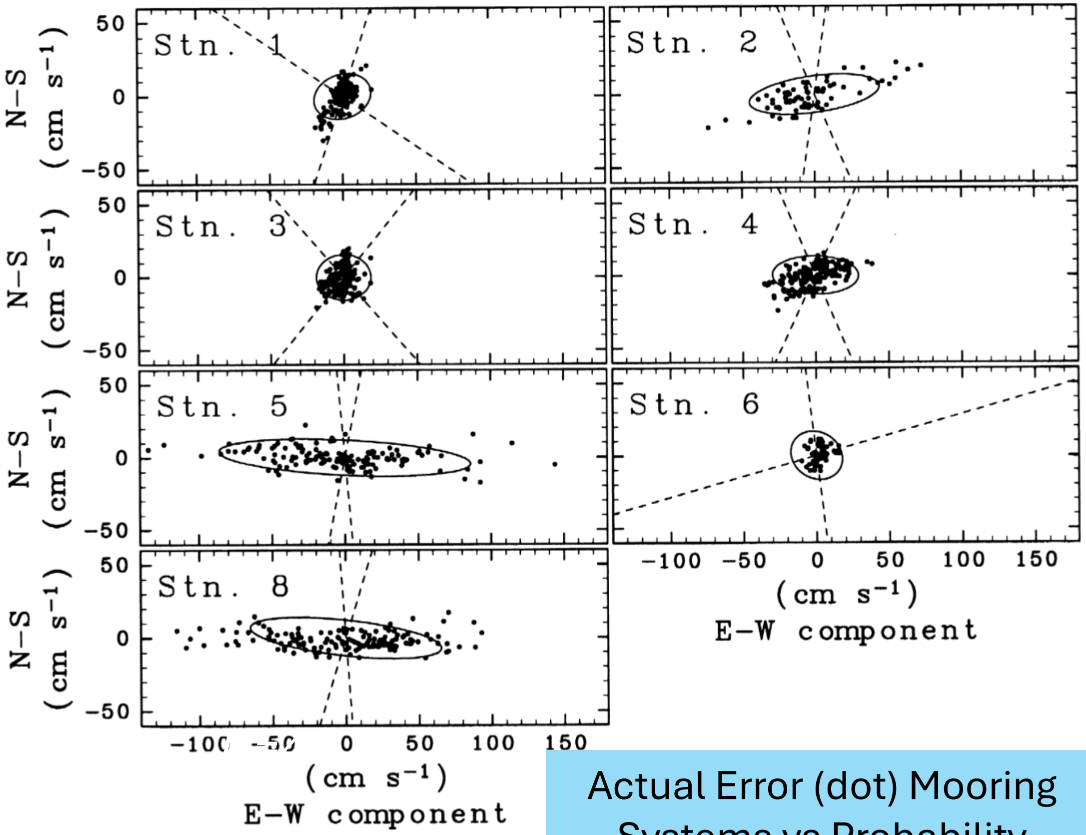
図　海洋レーダーシステム
（MLIT; 観測エリアおよび機器について）

	役割	参考論文
1	津波モニタリング	Hinata et al. 2011; Lipa et al. 2011; Dzvonkovskaya 2012 様々な場所で2011年東北沖地震の津波起因流速をHFレーダーが観測。
2	津波検知	Fuji and Hinata 2017; Ogata et al. 2018; 玉山2025 相互相関に基づく手法や機械学習を用いた手法によって津波を検知する。
3	津波予測	木村ら2018; Toguchi 2020; Mulia et al. 2020; Wang et al. 2023, 2024; Sahana et al. 2024 観測された流速をOI法でデータ同化することで、沿岸の津波波高を予測することが可能となる。

背景：海洋レーダーによる流速観測に影響を与える要因







(Nadai et al., 1999) Probability Density Distribution of Error Vector (Ellipse Theory)

Actual Error (dot) Mooring Systems vs Probability density error

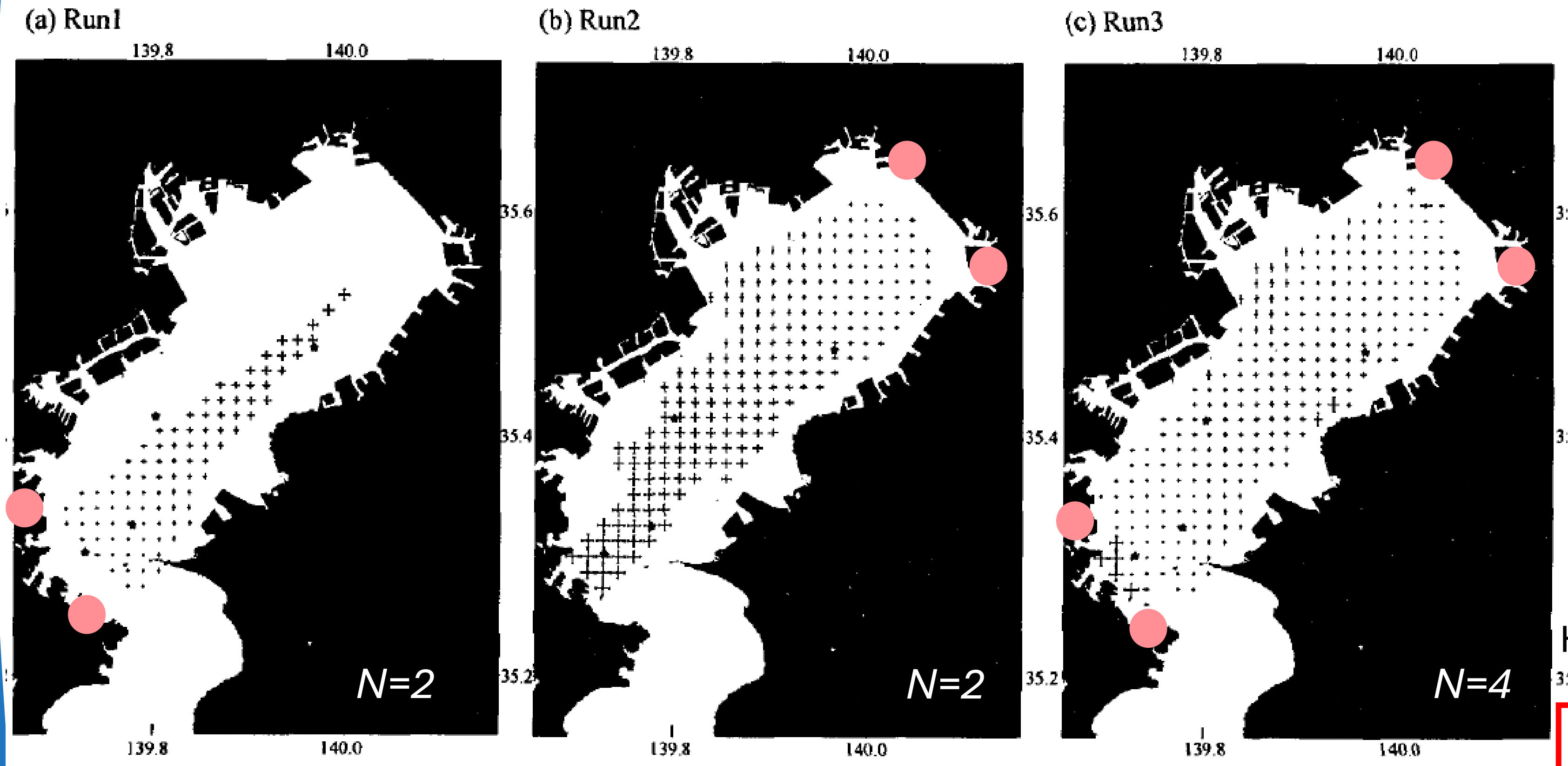
$$\sigma_u^2(\sin^2\theta_1 + \sin^2\theta_2) + 2\sigma_u\sigma_v(\sin\theta_1\cos\theta_1 + \sin\theta_2\cos\theta_2) + \sigma_v^2(\cos^2\theta_1 - \cos^2\theta_2)$$
$$= -2\sigma_r^2 \log\left(\frac{2\pi\sigma_r^2}{|\sin(\theta_1 - \theta_2)|}p\right)$$

Where, p is $0 < p \leq |\sin(\theta_1 - \theta_2)|/2\pi\sigma_r^2$

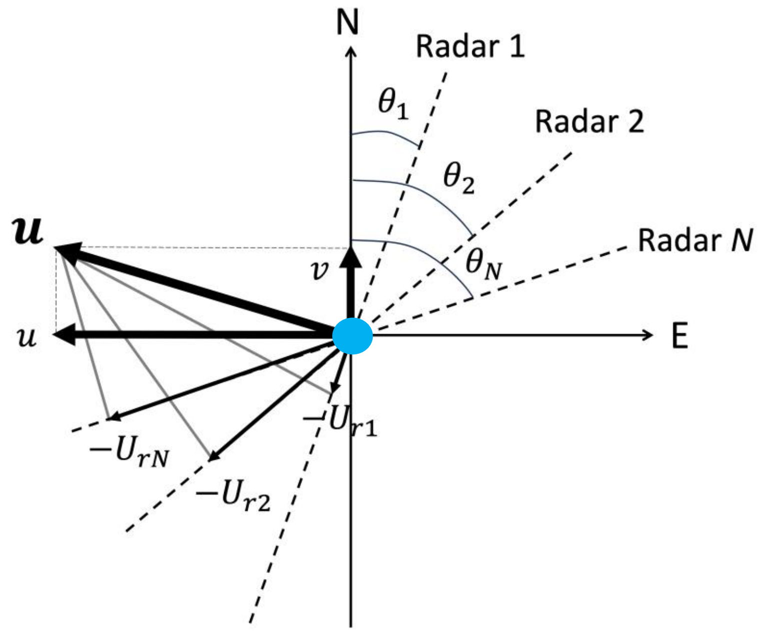
Where,
σ_u, σ_v = East-west and north-south measurement errors.

σ_r	= **Radial velocity error** of n^{th} radar.
θ_n	= **Direction of beam** to north of n^{th} radar.

背景：海洋レーダーによる流速観測に影響を与える要因



(Hinata et al., 2005)



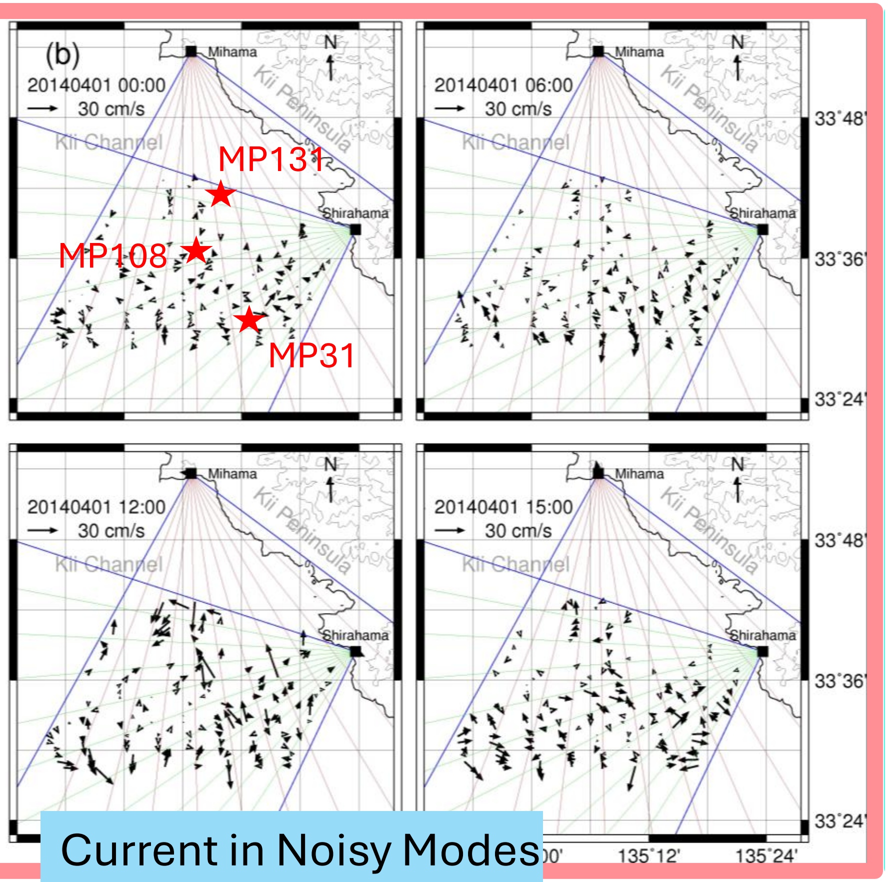
HF radar geometry in a measurement point

$$\begin{pmatrix}\sigma_u^2\\ \sigma_v^2\end{pmatrix} = \frac{1}{\sum_{n=1}^{N}\frac{\sin^2\theta_n}{\sigma_{rn}^2}\times\sum_{n=1}^{N}\frac{\cos^2\theta_n}{\sigma_{rn}^2}-\left[\sum_{n=1}^{N}\frac{\sin\theta_n\cos\theta_n}{\sigma_{rn}^2}\right]^2}\times\begin{bmatrix}\displaystyle\sum_{n=1}^{N}\frac{\cos^2\theta_n}{\sigma_{rn}^2}\\ \displaystyle\sum_{n=1}^{N}\frac{\sin^2\theta_n}{\sigma_{rn}^2}\end{bmatrix}$$

- N = **Number of radar.**
- σ_u, σ_v = East-west and north-south measurement errors.
- σ_{rn} = **Radial velocity error** of n^{th} radar.
- θ_n = **Direction of beam** to north of n^{th} radar.

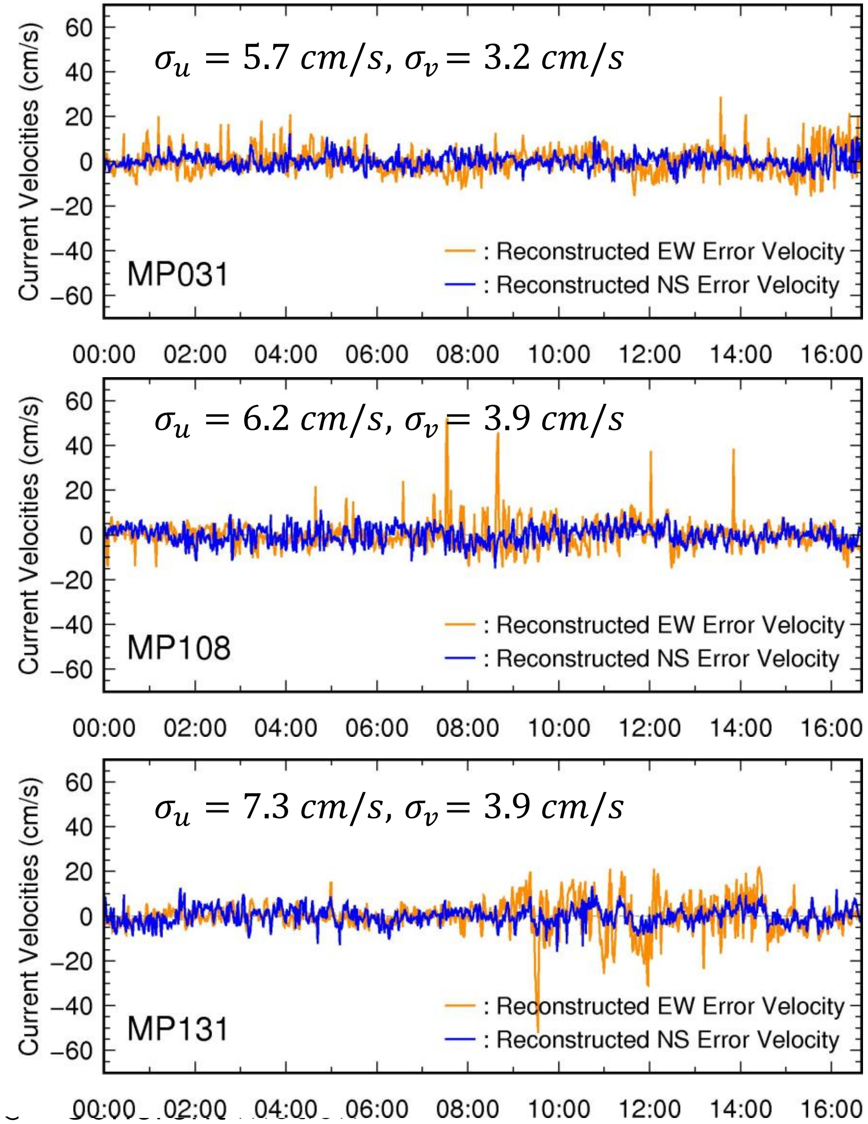
背景：海洋レーダーのEW・NS成分における非一様な観測誤差

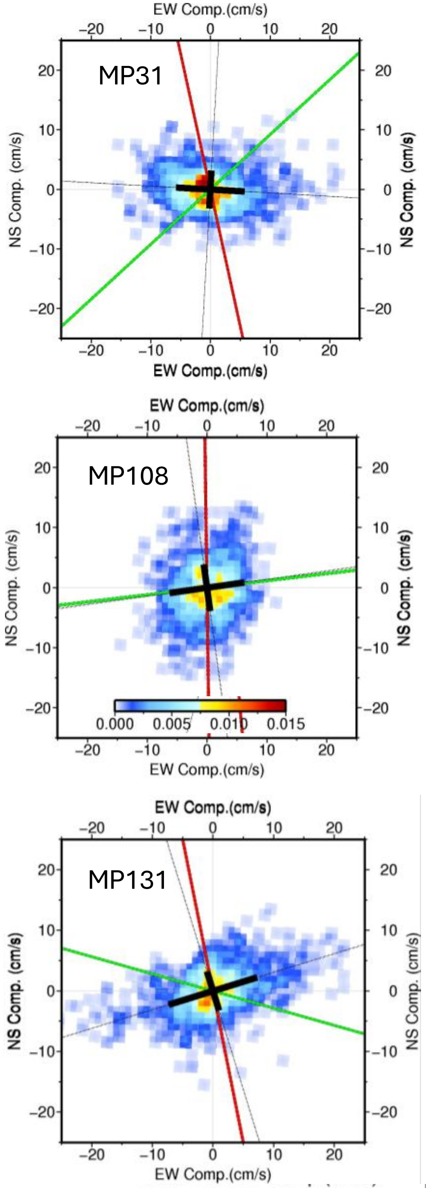
Data Period → April 1st, 2014; 00:00-16:39 JST (1-min Interval Time)



Current in Noisy Modes

- The current magnitude of noisy fields are **relatively much smaller** compared to physical fields
- **Inconsistent** motion

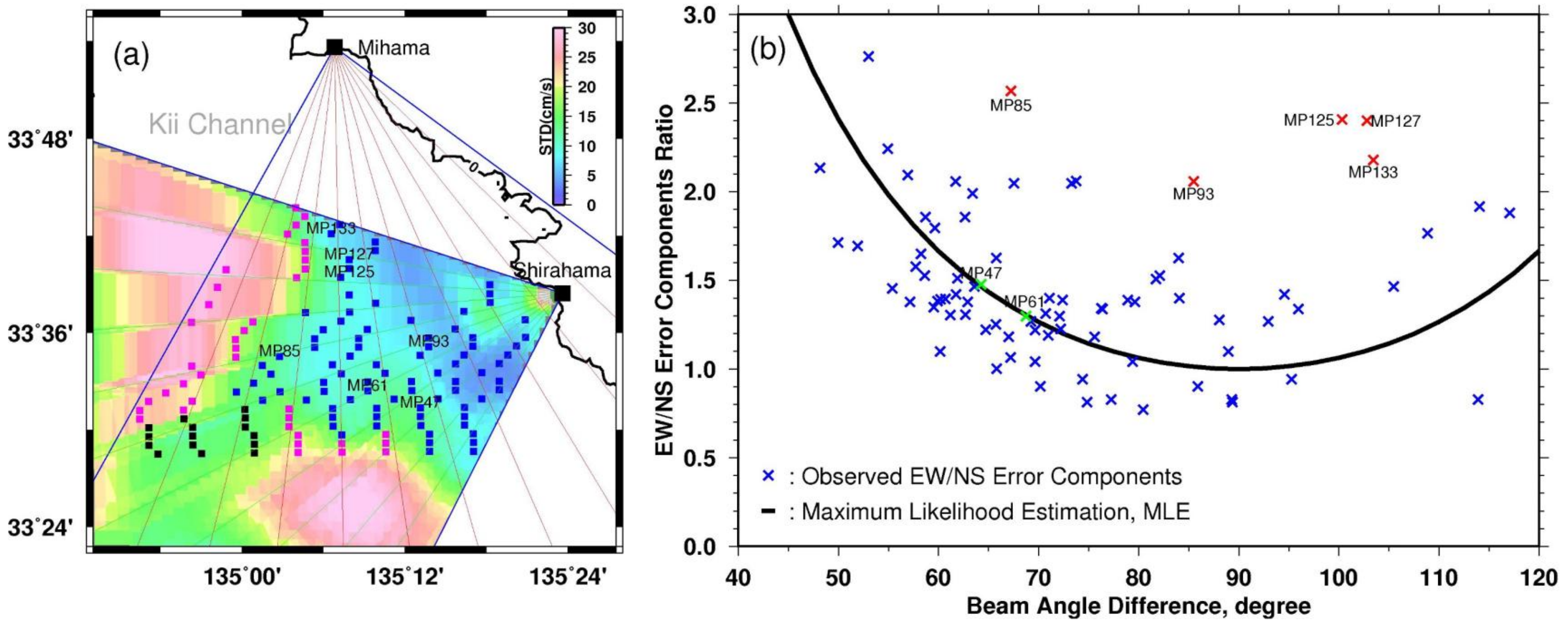




背景：海洋レーダーのEW・NS成分における非一様な観測誤差

Measurement Errors Estimation by Maximum Likelihood Estimation Theory (Hinata et al., 2005)

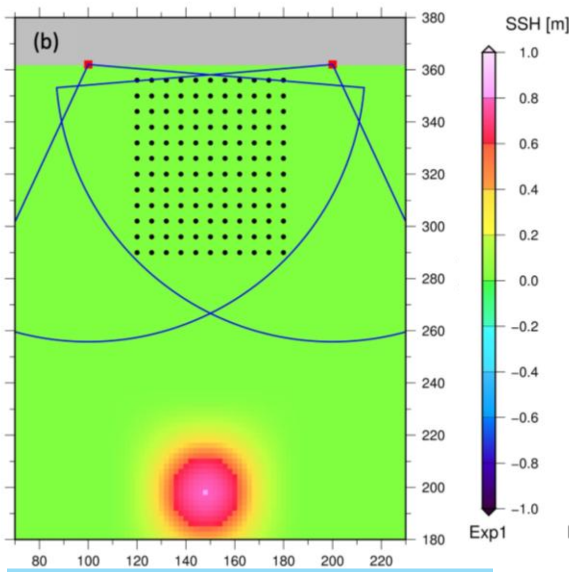
- Not all the 137 points show σ_u/σ_v ratios that aligned with the theory.
- 53 points (**black** and **purple**) were excluded from the comparison.
  - ✓ The points where the SNR was less than 25 dB (**black points**)
  - ✓ The standard deviation of the radial velocity exceeded 15 cm/s (**purple** points), based on the Shirahama radar measurements.

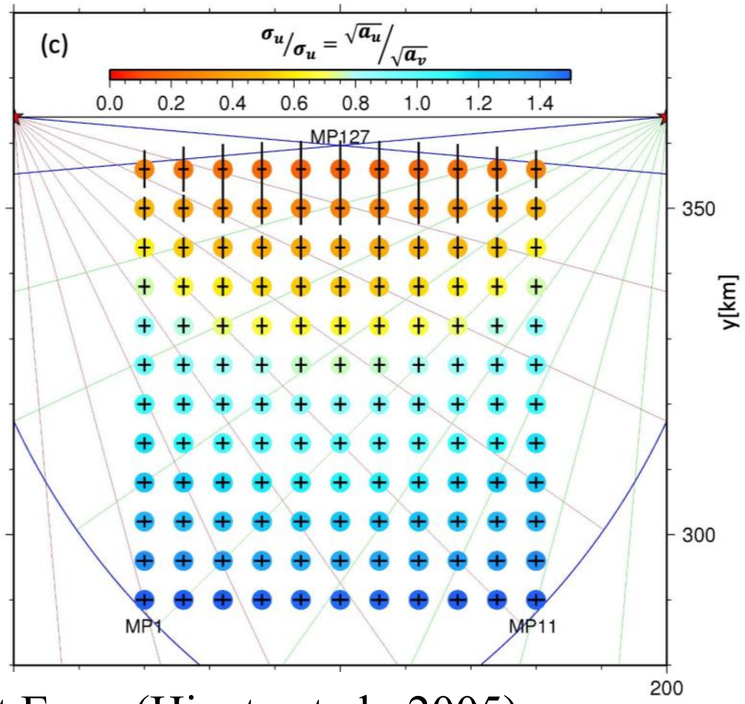


Since **the error measurements (σ_u, σ_v) is location dependent**, estimation of spatial distribution of σ_u and σ_v is **important for data assimilation**.

- 84 points (**blue**) were used for the comparison
  - ✓ Some points (MP85, MP93, MP133, MP125, MP127) **deviated** from the theory
  - ✓ Most of points **aligned well** with the MLE theory

背景：最適内挿法に基づくデータ同化への観測誤差空間分布の組み込み





1-m initial tsunami height
500 m flat bottom

Estimation of Measurement Error (Hinata et al., 2005)

$$\begin{pmatrix}\sigma_{u,i}^{o}\\ \sigma_{v,i}^{o}\end{pmatrix}^2 = \frac{1}{\left[\sum_{n=1}^{N} cos^2\theta_{n,i} \times \sum_{n=1}^{N} sin^2\theta_{n,i}\right] - \left[\sum_{n=1}^{N} \sin\theta_{n,i}\cos\theta_{n,i}\right]^2} \times \begin{pmatrix}\sum_{n=1}^{N} cos^2\theta_{n,i}\\ \sum_{n=1}^{N} sin^2\theta_{n,i}\end{pmatrix} \times \sigma_r^2 \quad (\mathrm{N}=2)$$

$$(\sigma_{u,i}^o)^2 = a_{u,i} \times (\sigma_r^o)^2, \qquad (\sigma_{v,i}^o)^2 = a_{v,i} \times (\sigma_r^o)^2$$

a =amplification factor

Data Assimilation with Optimal Interpolation

$$X_m^a = X_m^f + W\left[y_m - HX_m^f\right]$$

Weight Calculation *with Consideration of Spatial Distribution of Measurement Errors (*W_{gj} *for U ≠* W_{gj} *for V)*

$$\begin{cases} \sum_{j=1}^{132} w_{u,gj}\left(\mu_{ij}^b + \mu_{ij}^o \rho_{u,i}\rho_{u,j}\right) = \mu_{gi}^b \\ \sum_{j=1}^{132} w_{v,gj}\left(\mu_{ij}^b + \mu_{ij}^o \rho_{v,i}\rho_{v,j}\right) = \mu_{gi}^b \end{cases}$$

$$W_{u,gj} \neq W_{v,gj}$$

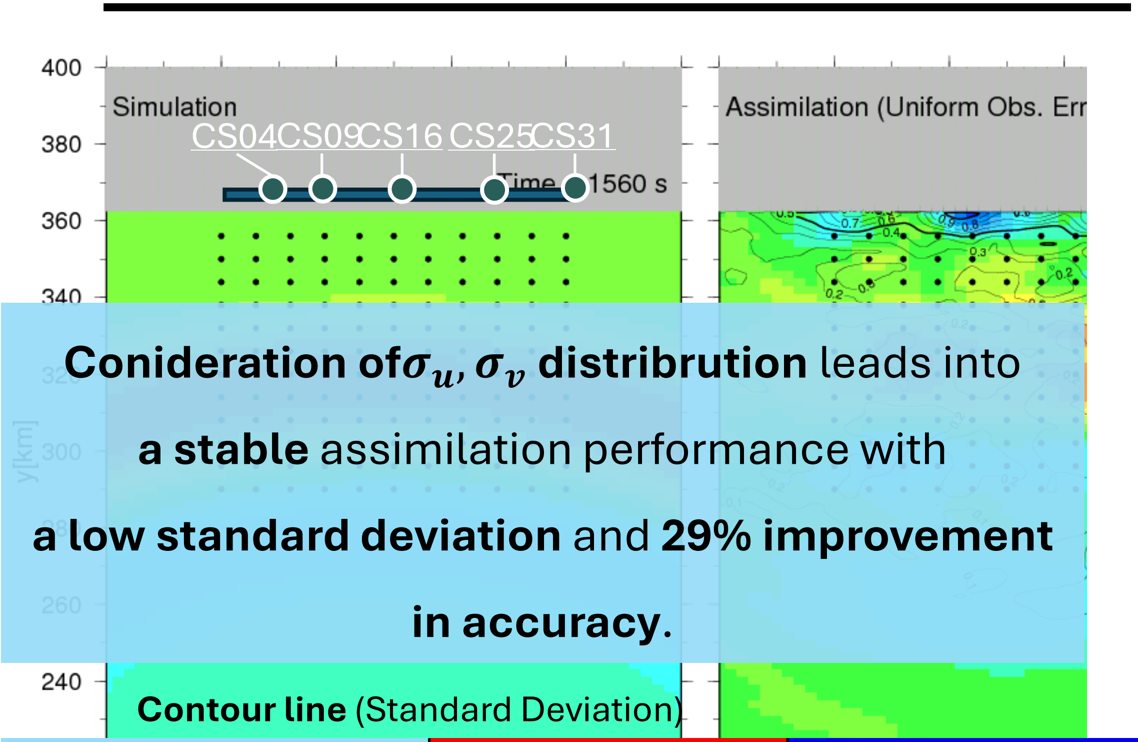
Where

$$\rho_{u,i} = \frac{\sigma_{u,i}^o}{\sigma_{u,i}^b} = \frac{\sqrt{a_{u,i}} \times \sigma_r^o}{\sigma_r^o} = \sqrt{a_{u,i}}$$

$$\rho_{v,i} = \frac{\sigma_{v,i}^o}{\sigma_{v,i}^b} = \frac{\sqrt{a_{v,i}} \times \sigma_r^o}{\sigma_r^o} = \sqrt{a_{v,i}}$$

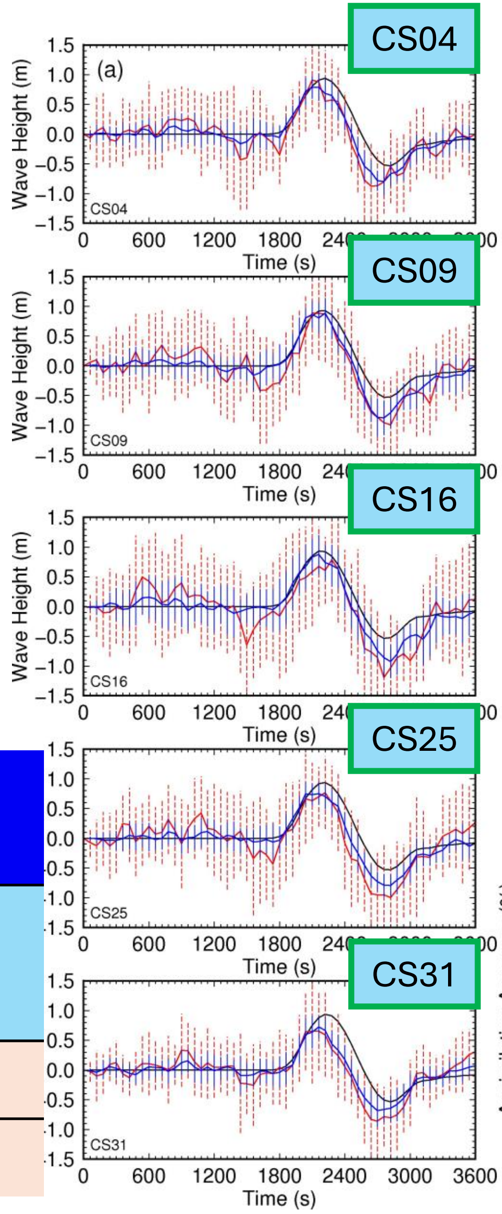
(Sahana et al., *2024*)

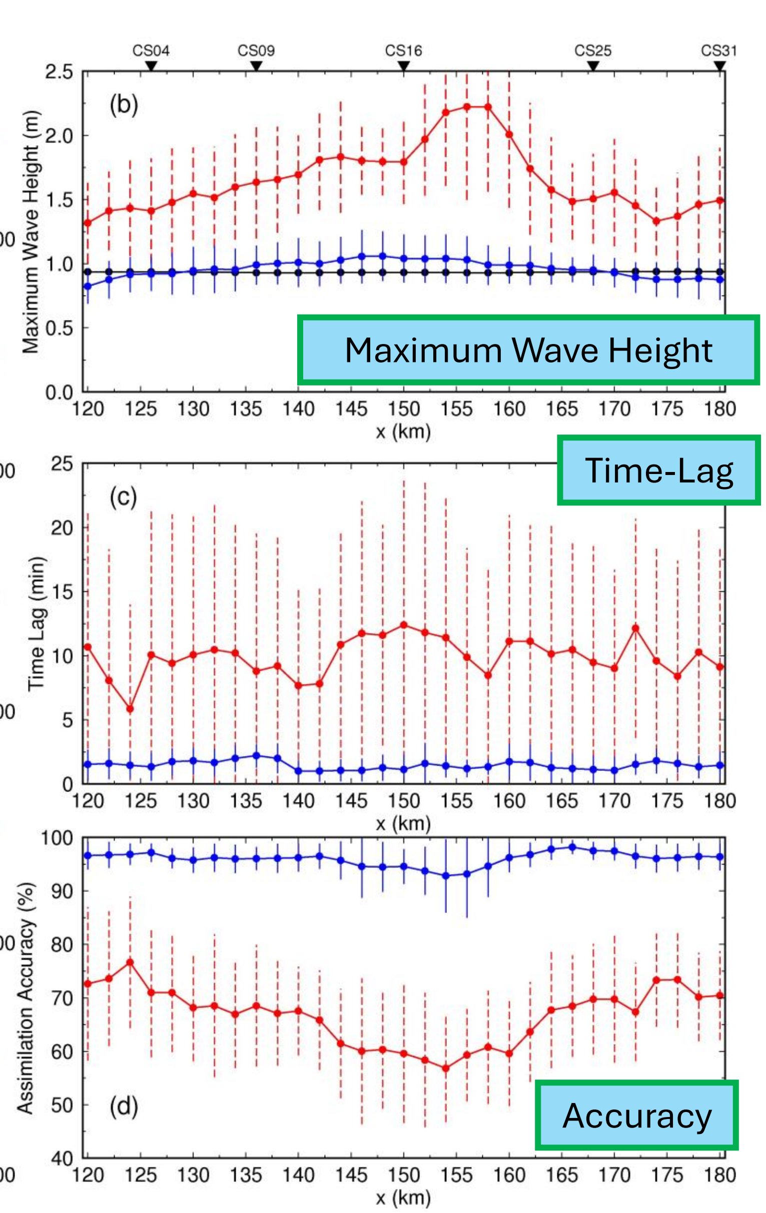
背景：最適内挿法に基づくデータ同化への観測誤差空間分布の組み込み



Conideration of σ_u, σ_v distribrution leads into **a stable** assimilation performance with **a low standard deviation** and **29% improvement in accuracy**.

	Uniform Case	Non-uniform Case
Accuracy (%)	57~77	93~98
SD (%)	8.7~15.1	1.4~8.6
Ave. Accuracy (%)	66.7	95.9
Ave. SD (%)	15.2	3.2





本研究の目的

- 現実の津波は、浅海域へ進入する際に浅水変形（shoaling）・屈折・反射など、地形の影響を強く受ける。
- 本研究では、海底地形が津波およびノイズ由来の津波様信号(Noise-induced tsunami signals)の伝播に与える影響を明らかにすることを目的とする。

本研究で実施した解析

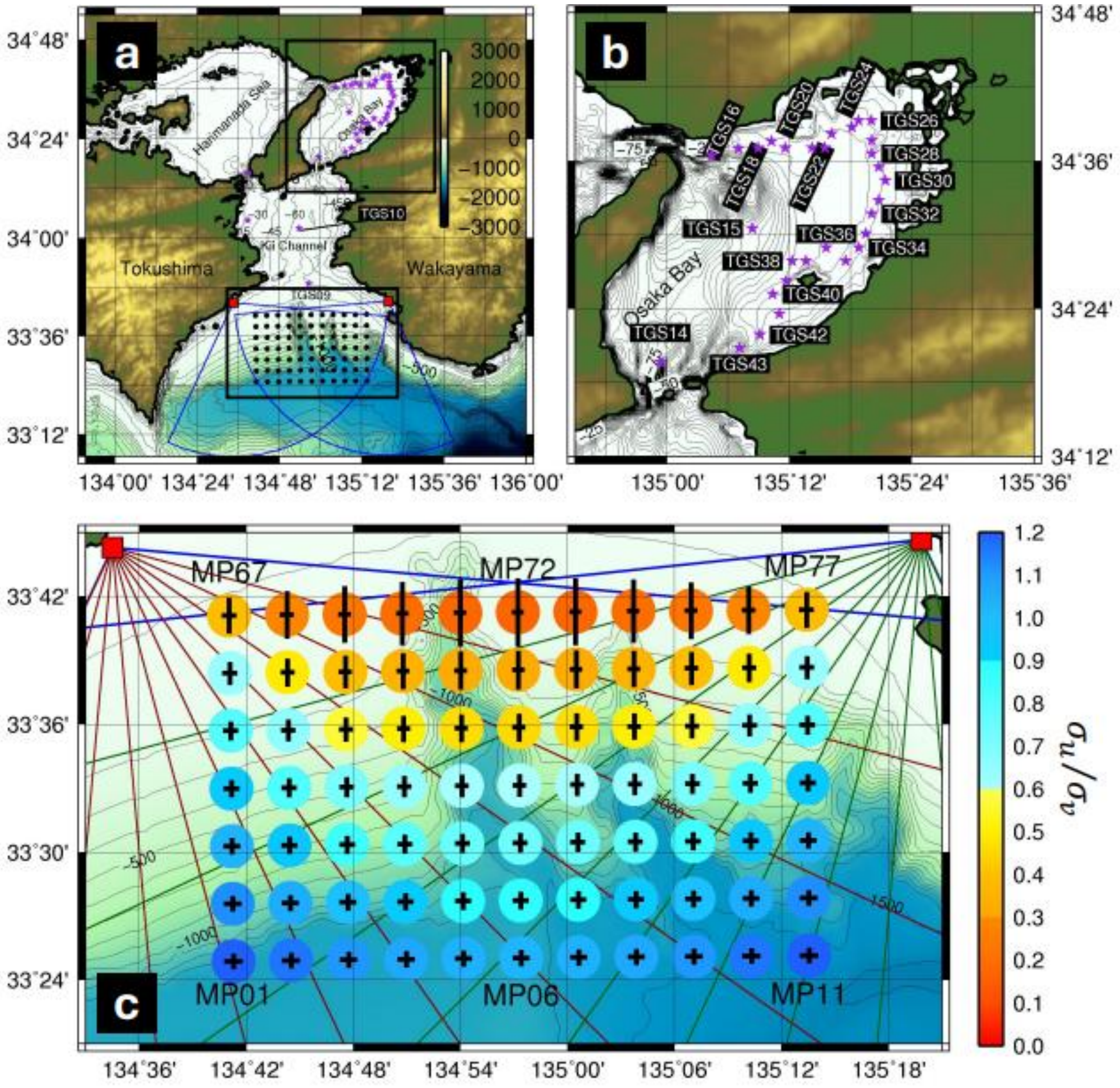
1. **南海トラフ地震（Case 4）による津波起因表面流速のデータ同化**
   → 地形が津波予測に与える影響の評価

昨年度の
海洋レーダー研究集会

2. **エネルギー線解析（Energy Ray Distribution）**
   → 地形による波の進行方向変化（集中・散乱）の把握
3. **ノイズ起因表面流速のデータ同化**
   → 測定誤差がどのように伝播するかの検証

本日の発表

方法：海洋レーダー・紀伊水道における地形的な特徴



紀伊水道の地形的特徴

1. **A deep central trench** flanked by **shallower** eastern and western coasts
   中央部に深い海底谷があり、東西の沿岸域は浅い地形となっている。
2. **Two narrow straits** connecting the Kii Channel to Osaka Bay and to Harimanada Sea
   紀伊水道と大阪湾、そして播磨灘を結ぶ2つの狭い海峡が存在する。

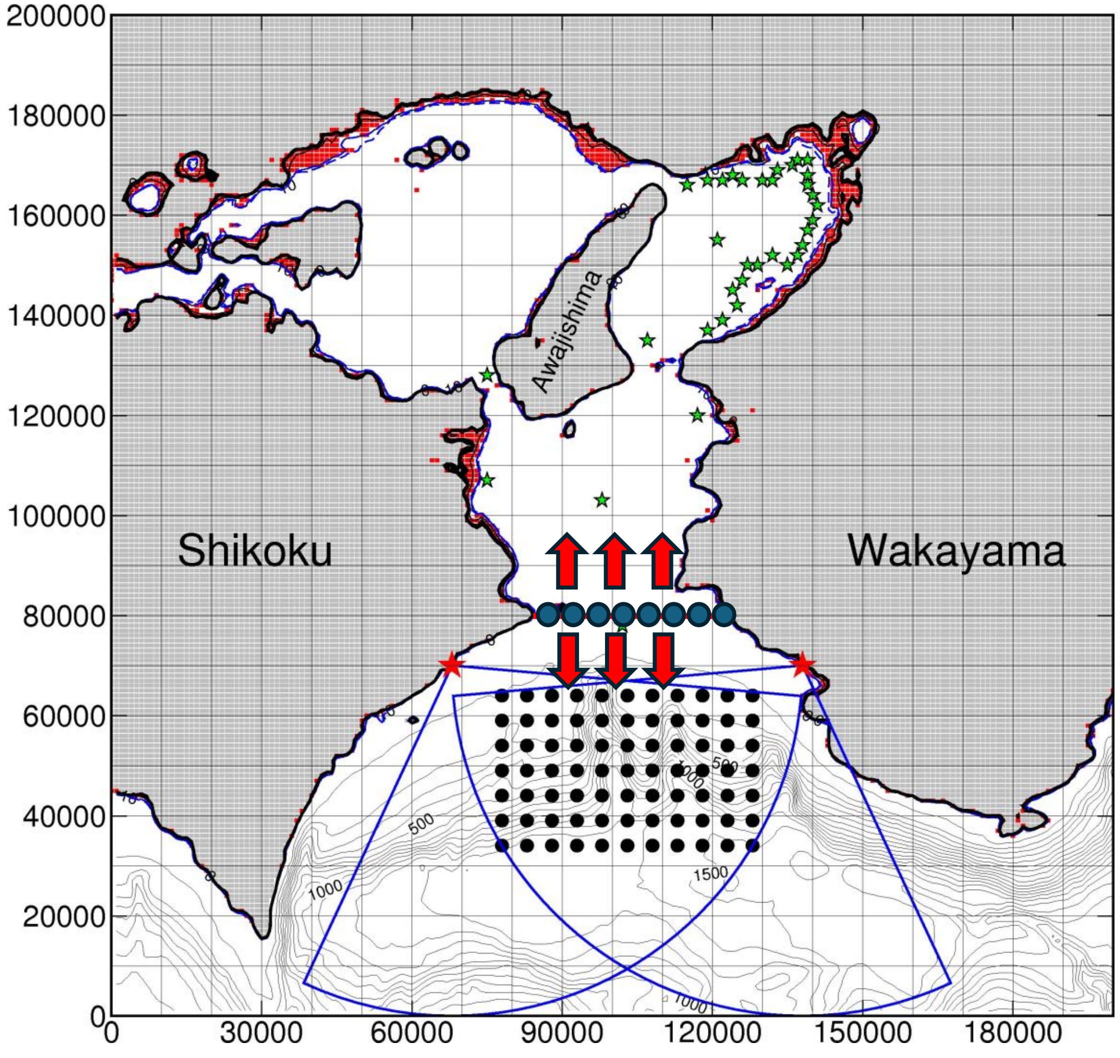
測定誤差の推定（日向ら、2005）

$$\begin{pmatrix}\sigma_{u,i}^{o} \\ \sigma_{v,i}^{o}\end{pmatrix}^2 = \frac{1}{\left[\sum_{n=1}^{N} cos^2\theta_{n,i} \times \sum_{n=1}^{N} sin^2\theta_{n,i}\right] - \left[\sum_{n=1}^{N} \sin\theta_{n,i}\cos\theta_{n,i}\right]^2} \times \begin{pmatrix}\sum_{n=1}^{N} cos^2\theta_{n,i} \\ \sum_{n=1}^{N} sin^2\theta_{n,i}\end{pmatrix} \times \sigma_r^2 \quad (\mathrm{N}=2)$$

観測点の数は**77**点

MP72では$\sigma_u/\sigma_u \approx 0.2$
MP17では$\sigma_u/\sigma_u \approx 1.0$

方法：エネルギー線解析（Ray-Tracing Method）



Tsunami energy propagation (Satake, 1988)

To evaluate bathymetry effects along tsunami propagation paths.

$$d\theta/dT = 1/nR \cos\zeta \qquad d\varphi/dT = 1/nR\sin\theta \sin\zeta$$

$$\frac{d\zeta}{dT} = -\frac{\sin\zeta}{n^2R}\frac{\partial n}{\partial\theta} + \frac{\cos\zeta}{n^2R\sin\theta}\frac{\partial n}{\partial\varphi} - \frac{1}{nR}\sin\zeta\cot\theta$$

θ, φ = colatitude and longitude

ζ = ray direction (counter – clockwise from north)

R = radius of earth (6371 km)

n = slowness ($= 1/\sqrt{gh}$)

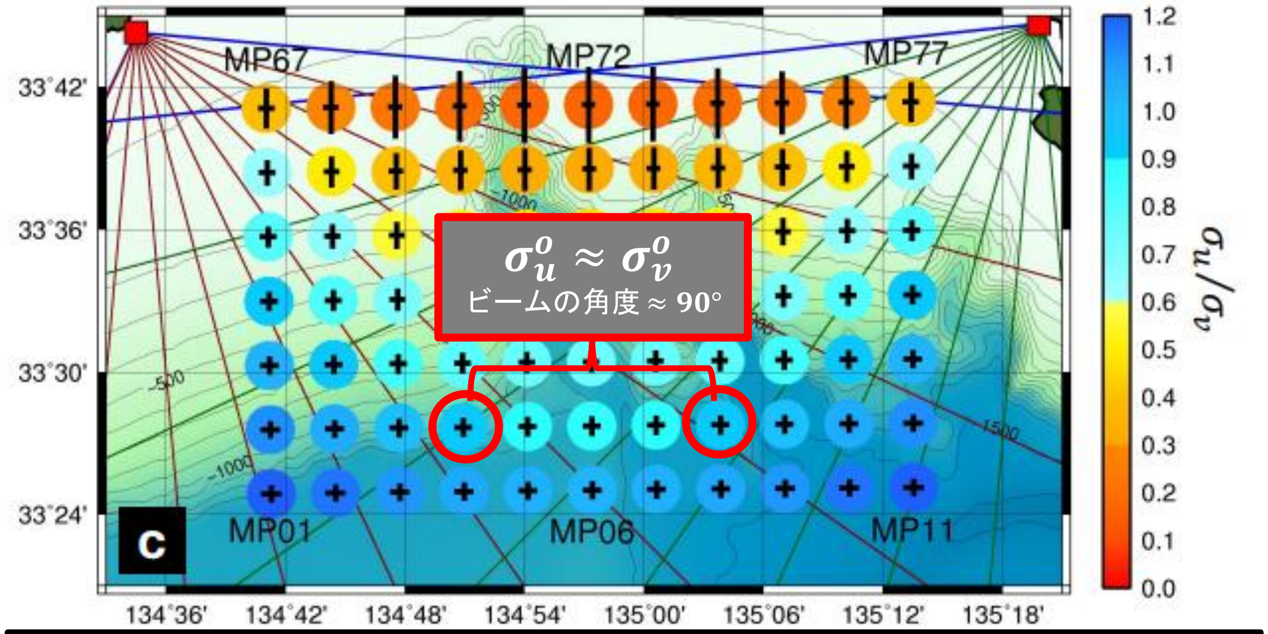
本研の計算条件：

- 紀伊水道に入るエネルギーを知るために、紀伊水道の入り口で **9** 点のスタートポイントを設定した。
- それぞれのポイントから360°（10°間隔）に波を伝播する。

Ray-tracingのプログラム (Gusman et al., 2017)

Source: [GitHub - adityagusman/tsunami-raytracing: MATLAB codes to trace tsunami rays from a point source]

方法：最適内挿法に基づくデータ同化への観測誤差空間分布の組み込み



Estimated Measurement Errors 測定誤差の推定 σ_u, σ_v (Hinata et al., 2005)

$$\begin{pmatrix}\sigma_{u,i}^o \\ \sigma_{v,i}^o\end{pmatrix}^2 = \frac{1}{\left[\sum_{n=1}^{N} cos^2\theta_{n,i} \times \sum_{n=1}^{N} sin^2\theta_{n,i}\right] - \left[\sum_{n=1}^{N} \sin\theta_{n,i}\cos\theta_{n,i}\right]^2} \times \begin{pmatrix}\sum_{n=1}^{N} cos^2\theta_{n,i} \\ \sum_{n=1}^{N} sin^2\theta_{n,i}\end{pmatrix} \times \sigma_r^2 \qquad N = 2.$$

$$\left(\sigma_{u,i}^o\right)^2 = a_{u,i} \times (\sigma_r^o)^2, \qquad \left(\sigma_{v,i}^o\right)^2 = a_{v,i} \times (\sigma_r^o)^2$$

a =amplification factor

Data Assimilation with Optimal Interpolation

$$X_m^a = X_m^f + W\left[y_m - HX_m^f\right]$$

Weight Calculation with Consideration of Spatial Distribution of Measurement Errors (W_{gj} for U ≠ W_{gj} for V)

$$\begin{cases} \sum_{j=1}^{77} w_{u,gj}\left(\mu_{ij}^b + \mu_{ij}^o \rho_{u,i}\rho_{u,j}\right) = \mu_{gi}^b \\ \sum_{j=1}^{77} w_{v,gj}\left(\mu_{ij}^b + \mu_{ij}^o \rho_{v,i}\rho_{v,j}\right) = \mu_{gi}^b \end{cases}$$

Where

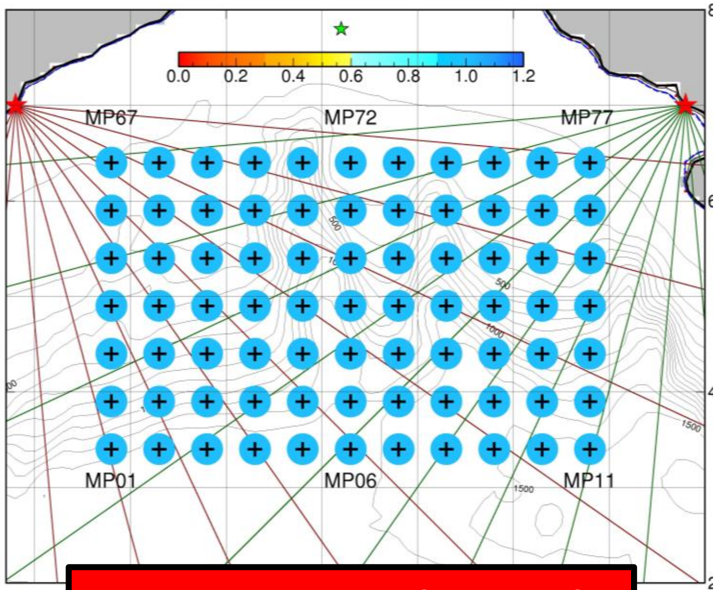
Nonuniformity of Obs Errors

$$\rho_{u,i} = \frac{\sigma_{u,i}^o}{\sigma_{u,i}^b} = \frac{\sqrt{a_{u,i}} \times \sigma_r^o}{\sigma_r^o} = \sqrt{a_{u,i}}$$

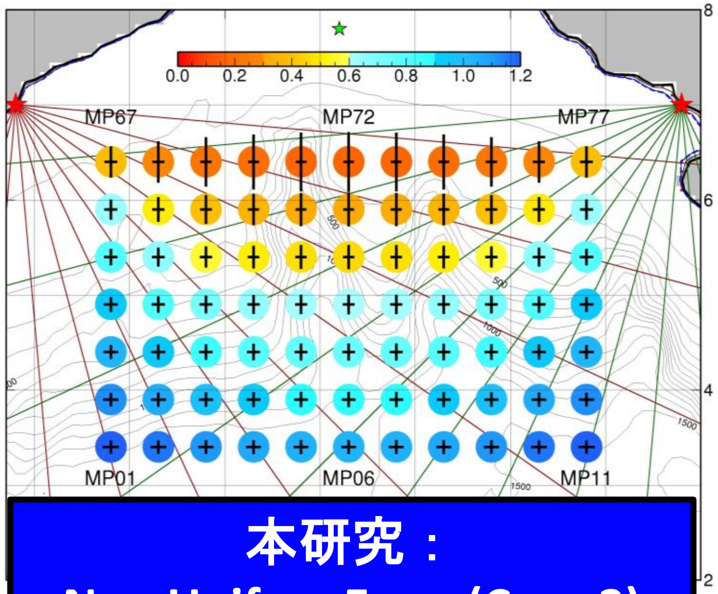
$$\rho_{v,i} = \frac{\sigma_{v,i}^o}{\sigma_{v,i}^b} = \frac{\sqrt{a_{v,i}} \times \sigma_r^o}{\sigma_r^o} = \sqrt{a_{v,i}}$$

(Sahana et al., *2024*)

方法：ノイズ誘発津波（観測誤差）のデータ同化と予測



Unifom Error (Case 1)



本研究：
Non Unifom Error (Case 2)

$$\sum_{j=1}^{m} W_{gj}\left(\mu_{ij}^{o}\rho_i\rho_j + \mu_{ij}^{b}\right) = \mu_{gi}^{b}$$

$\rho_i = \rho_j = \frac{\sigma^o}{\sigma^B}$ = 1 (uniform)

W_{gj} for U = W_{gj} for V

For U $$\sum_{j=1}^{m} W_{gj}\left(\mu_{ij}^{o}\rho_i\rho_j + \mu_{ij}^{b}\right) = \mu_{gi}^{b}$$

$\rho_i = \rho_j = \frac{\sigma_u^o}{\sigma^B} \neq 1$ (not-uniform, θ)

For V $$\sum_{j=1}^{m} W_{gj}\left(\mu_{ij}^{o}\rho_i\rho_j + \mu_{ij}^{b}\right) = \mu_{gi}^{b}$$

$\rho_i = \rho_j = \frac{\sigma_v^o}{\sigma^B} \neq 1$ (not-uniform, θ)

W_{gj} for U ≠ W_{gj} for V

Data Assimilation with Optimal Interpolation

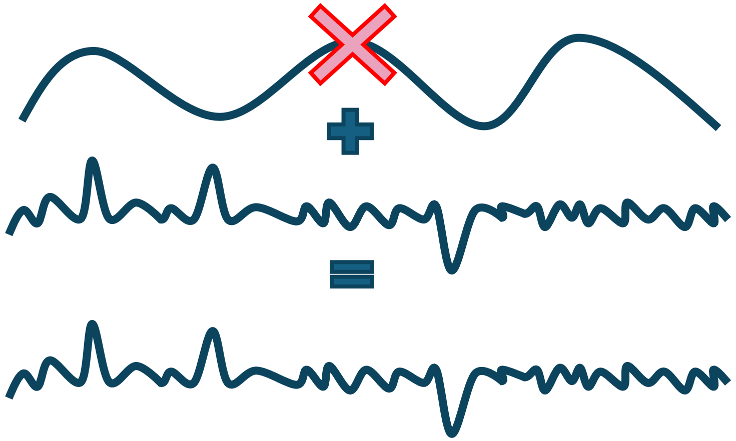
$$X_m^a = X_m^f + W\left[y_m - HX_m^f\right]$$

About observation data y_m → u_{obs}, v_{obs}

$$y_{u,i}^{o} = u_{sim\_un,i} + \sigma_{u,i}^{o} = rand.(\sqrt{a_{u,i}} \times \sigma_r^o)$$

$$y_{v,i}^{o} = v_{sim\_un,i} + \sigma_{v,i}^{o} = rand.(\sqrt{a_{v,i}} \times \sigma_r^o)$$

Where, σ_r^o = 5 cm/s (velocity resolution)



結果：Energy distribution in Kii Channel

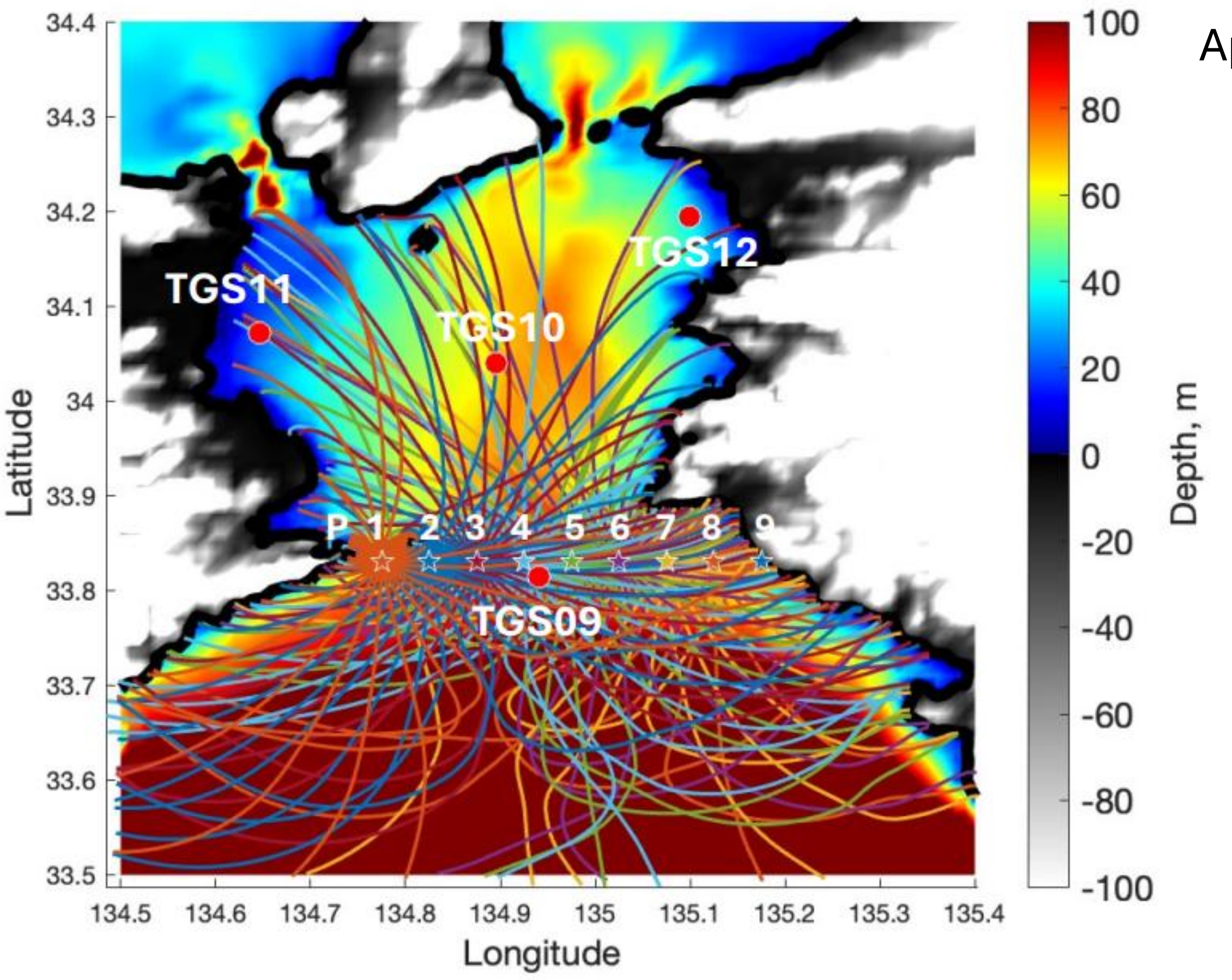


Fig. 5. Tsunami ray tracing with multiple initial sources (star symbols) and propagation directions (0° to 360°) with 10° interval (colored lines).

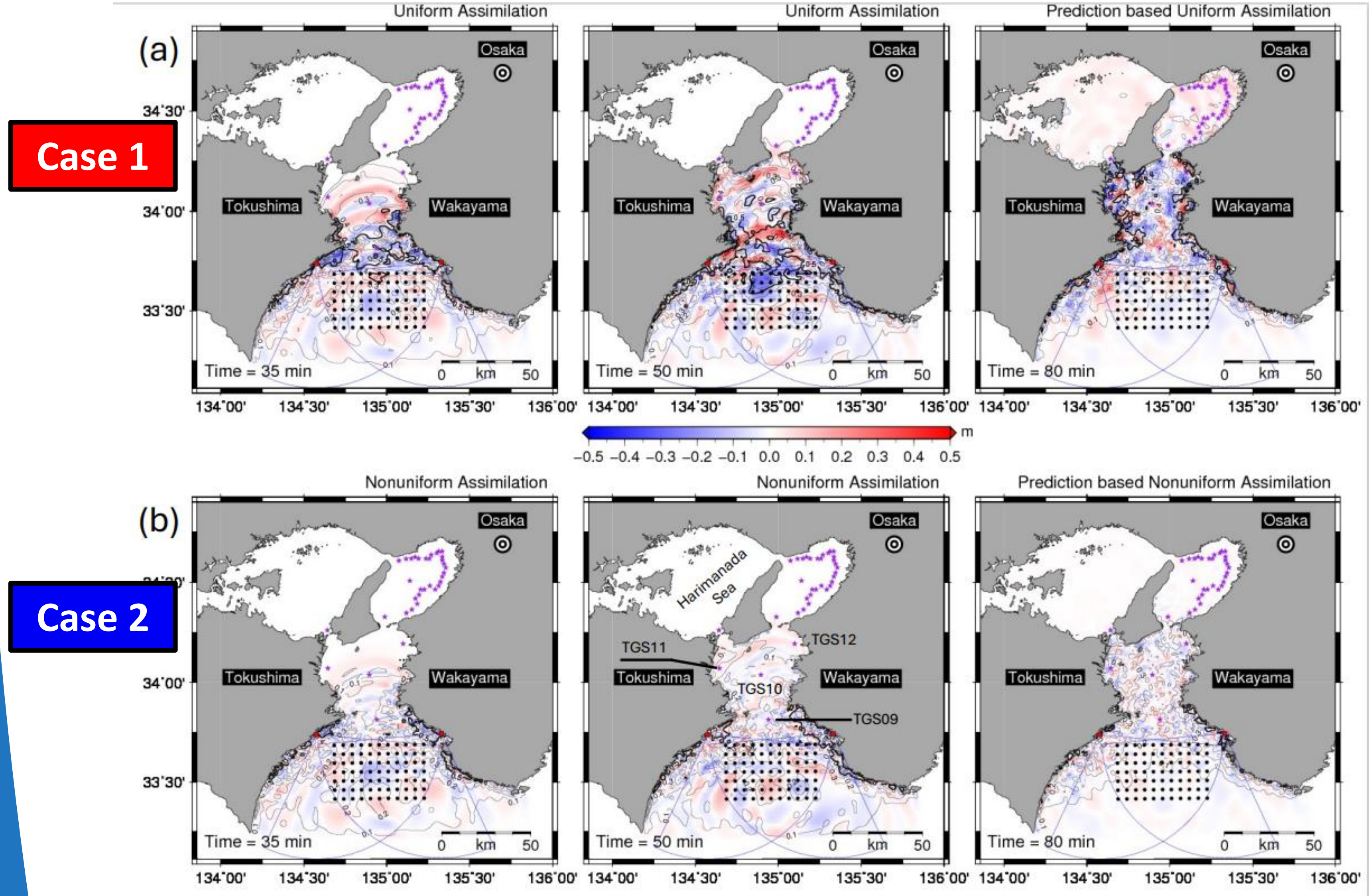
Applying Ray-tracing program by Gusman et al. (2017);

- Because the channel center is much deeper than the eastern and western coasts, tsunami energy is refracted toward both sides.
- The main energy pathway concentrates along the **west coast** rather than the east.
- As a result, **higher waves is expected to occur in western coast.**

- 水道中央部が東西の沿岸域よりも深いため、津波エネルギーは両側へ屈折する。
- 主なエネルギー経路は東側よりも西側沿岸に集中する。
- その結果、西側沿岸でより高い津波が発生すると予想される。

結果：ノイズ由来津波の一様・非一様伝播の比較（15回の計算）

Propagation of noise induced tsunamis in Case 1 (a) and Case 2 (b) at 35, 50, and 80 minutes across 15 times experiments



Colors (average wave height)

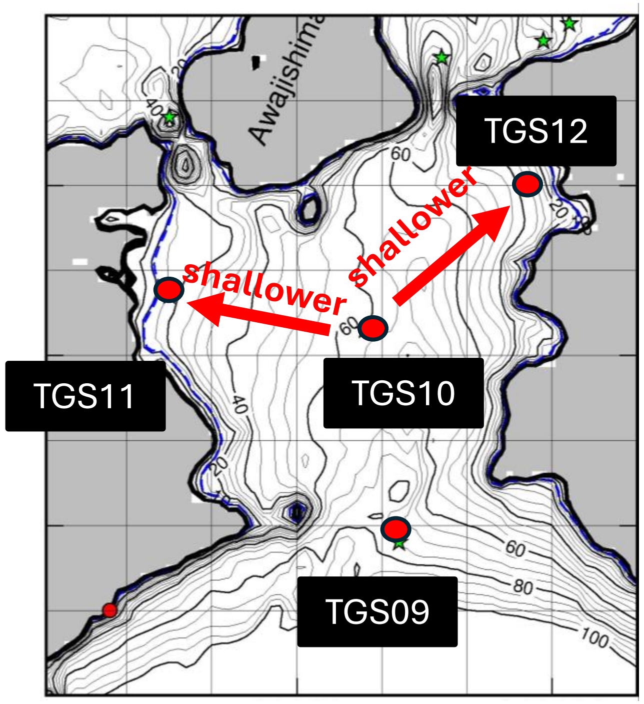
Contour line (Standard Deviation)

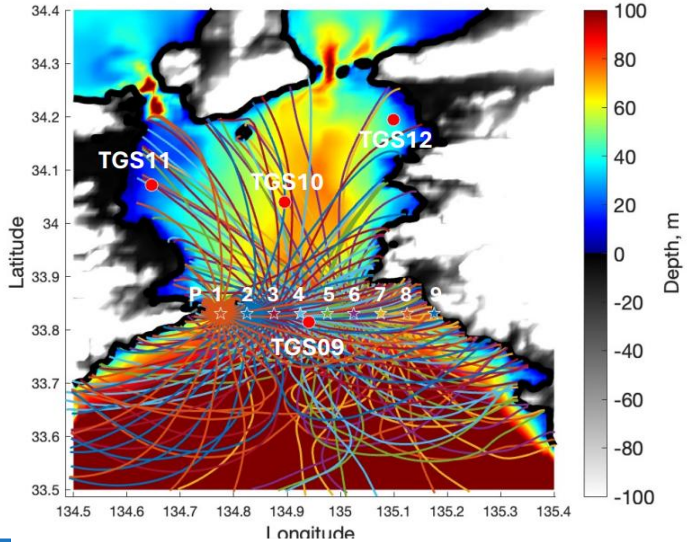
Every 0.5 m

Every 0.1 m

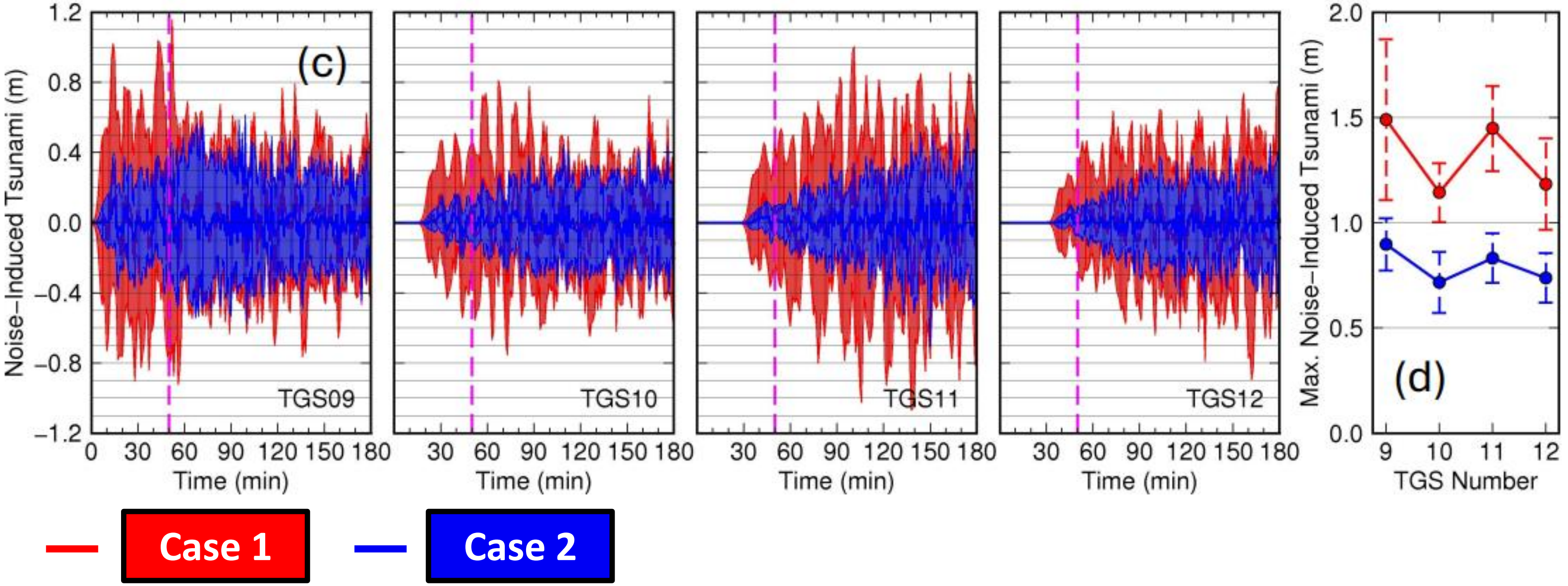
- **Uniform vs Non-Uniform cases:** Uniform amplification of noise-induced tsunamis (SDs up to 0.5 m); non-uniform suppresses noise (<0.1 m).
- **Bathymetry:** Deep trench and shallow coasts cause refraction/shoaling, enhancing SSH fluctuations in uniform case.
- **Forecast Stability:** Narrow straits filter waves; non-uniform approach keeps SDs low, enabling reliable forecasts.

結果：ノイズ由来津波の一様・非一様伝播の比較（15回の計算）





Mean ± standard deviation of the time series (c) and maximum noise-induced tsunami height (d) at TGS09– TGS12 (red: uniform; Case1, blue: non-uniform; Case2).



Mean ± standard deviation of maximum noise-induced tsunami height at TGS10– TGS12 with water depth

観測地点	水深 (m)	Case 1（m）	Case 2（m）
TGS10	65	1.10 ± 0.12	0.70 ± 0.15
TGS11	22	1.45 ± 0.20	0.83 ± 0.12
TGS12	35	1.18 ± 0.22	0.74 ± 0.12

まとめ

- **Assimilating measurement errors together with ray-tracing helps identify regions where noise-induced tsunamis are likely to appear**, especially those originating from radar coverage areas—an important contribution to tsunami early-warning systems.
- **Noise-induced tsunami waves created localized fluctuations in both assimilated and forecasted heights**, mainly due to **refraction and shoaling**, highlighting the **critical role of bathymetry** in detecting areas with noisy or unreliable forecast performance.

- **観測誤差の同化とレイトレーシングを組み合わせることで、レーダー観測域を起点とするノイズ由来津波が発生しやすい領域を特定できる。** これは津波早期警戒システムに重要な示唆を与える。
- **ノイズ誘発津波は、同化後および予測された津波高に局所的な変動を生じさせた。** これらの変動は主に**屈折および浅水変形（ショーリング）によって発生し、海底地形がノイズや予測不確実性の高い領域を見極める上で極めて重要である**ことを示している。

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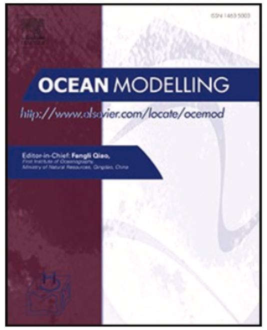

Tsunami data assimilation and forecast in the Kii Channel using high-frequency radar: Bathymetry effects on the propagation of measurement errors

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