

「はやぶさ」リエントリーの 地上観測

石原吉明（国立天文台 RISE月探査プロジェクト）

「はやぶさ」リエントリー地上観測チーム

本日のお話

- 観測の背景
 - 流星・火球・隕石落下の研究
 - カプセルリエントリーは隕石落下である
- オーストラリアでの観測
 - WPA見渡す限り地平線・4WDで疾走
 - 観測点設置
- 取得データ・初期解析結果の紹介
 - リエントリー画像・動画
 - 音も聴こえた！！
 - インフラサウンド・地震計測結果

流星・火球

- 最も馴染み深く、親しまれている天文現象
 - しし座 γ 流星群やペルセウス座 γ 流星群などの群流星や散在流星
- 流星体が地球大気と衝突し発光する現象
- 一般に金星よりも明るい流星を火球と呼ぶ
- ごく希に燃え尽きずに地表に達したのが「隕石」

流星研究 -1-

- 群流星の出現予測

- しし座 γ 流星群などでは、流星体の軌道計算をもとに、数分-数十分程度の精度で予測可能

- 流星体の組成

- 流星の分光観測…
- Leonid MAC = 彗星観測との位置づけで1998-2002

- 落下経路

- パトロールカメラ (写真・ビデオ)
- 北米・ヨーロッパでは軍事衛星によるIRデータ<=データアクセスに問題
- 目撃証言=精度の点に問題

流星研究 -2-

- 発光メカニズム・アブレーション
 - 一応理論はあるが、不明な点多数
 - 分光観測... 何が光っているのか？
- 落下中の流星体の挙動
 - まだまだよくわかっていない。
- 元となるデータ
 - 光学観測データ
- 光学データ以外に使えるデータは？

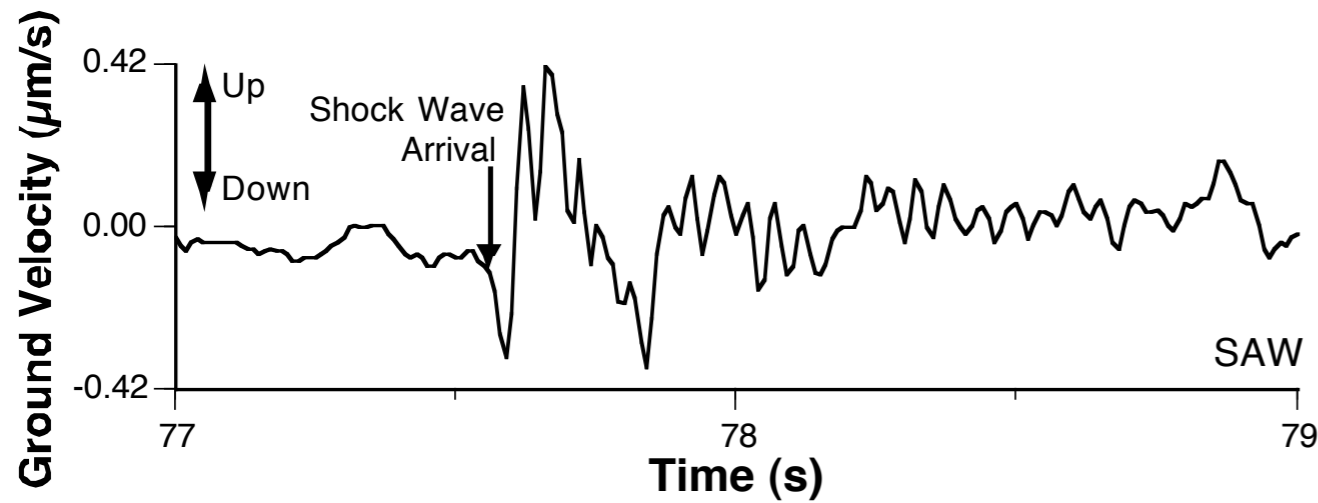
新たな流星研究 -1-

- 流星体が地球大気と衝突することにより…
 - 発光する現象
 - ✳️ 衝撃波を励起する現象
 - 流星はMeteoroidが超音速で大気中を飛行 (11-71km/s)
 - ◆ 波面が円錐形の衝撃波
 - Meteoroidは、内部衝撃波が自身の結合強度を上回ると、爆発分裂する。
 - ◆ 波面が球形の衝撃波

新たな流星研究 -2-

- 観測網の発達
 - 微気圧計測網
 - 核実験探知目的
 - 火山の爆発的噴火観測目的
 - 地震観測網
 - ◆ 衝撃波は地表に達すると地面とカップリングし地動を励起。
 - ◆ 微小地震観測を目的として展開された短周期地震計が地動を感知
- 衝撃波の到着時データ
 - 衝撃波を励起したMeteoroid(火球)の落下経路
- 衝撃波の振幅データ
 - 衝撃波の振幅は、流星体の大きさや速度に依存していると考えられる
 - AblationによるMeteoroidの落下中のサイズ変化を導き出せる可能性

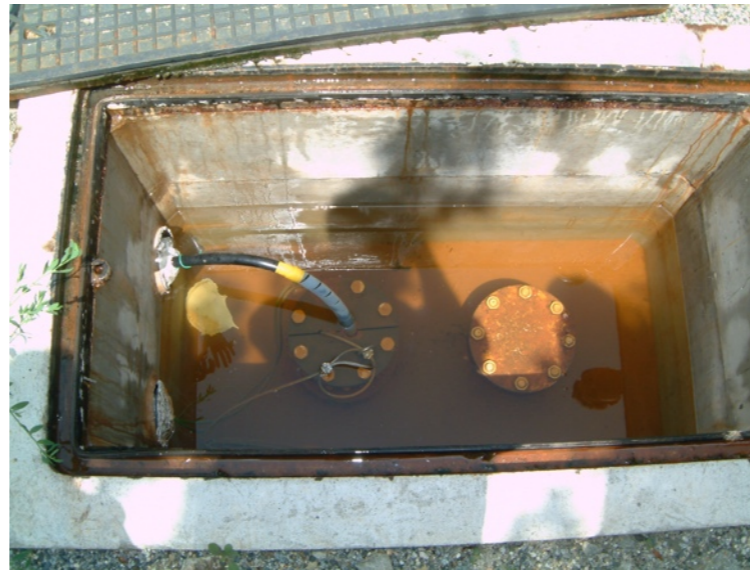
地震計に記録された衝撃波



1998年宮古火球による衝撃波が励起した地動
東北大学沢内観測点上下動成分の波形



気象庁

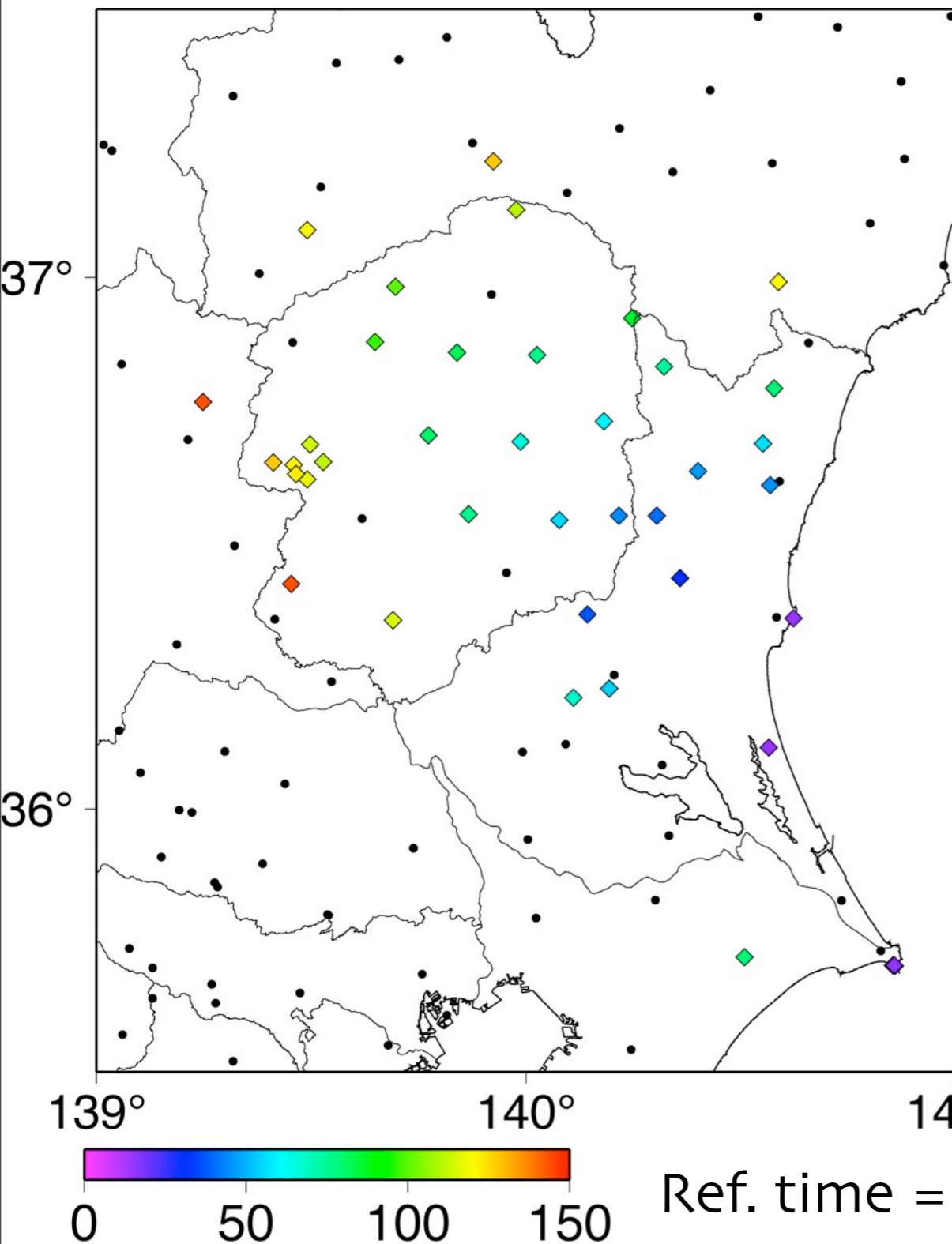


Hinet



大学関係

Seismic Detection of the 2003 Kanto Bolide



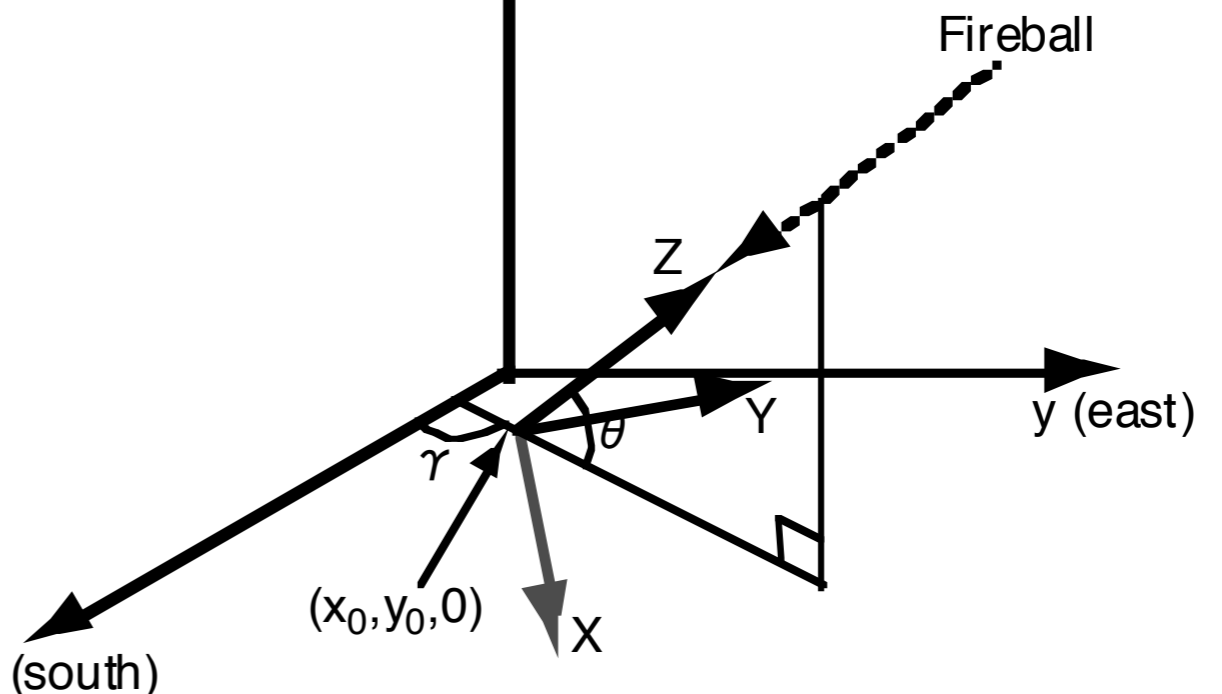
$$\frac{\sqrt{X^2 + Y^2}}{\tan \beta} - Z = v(t - t_0)$$

$$\sin \beta = c/v$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} \cos \gamma \sin \theta & \sin \gamma \sin \theta & -\cos \theta \\ -\sin \gamma & \cos \gamma & 0 \\ \cos \gamma \cos \theta & \sin \gamma \cos \theta & \sin \theta \end{pmatrix} \begin{pmatrix} x - x_0 \\ y - y_0 \\ z \end{pmatrix}$$

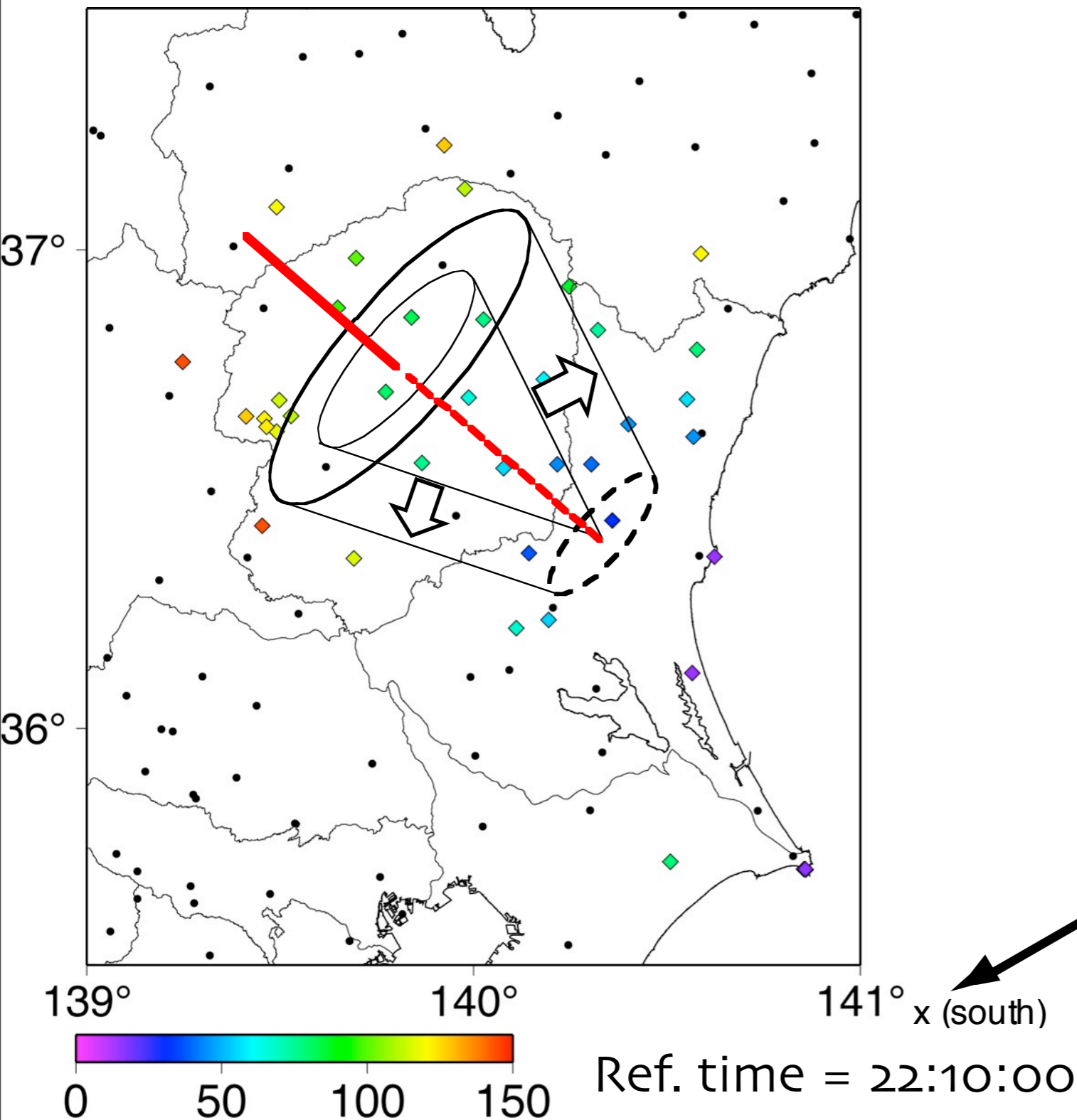
z (zenith)

Nagasawa and Miura (1986)



[Ishihara et al., 2004, GRL]

Seismic Detection of the 2003 Kanto Bolide



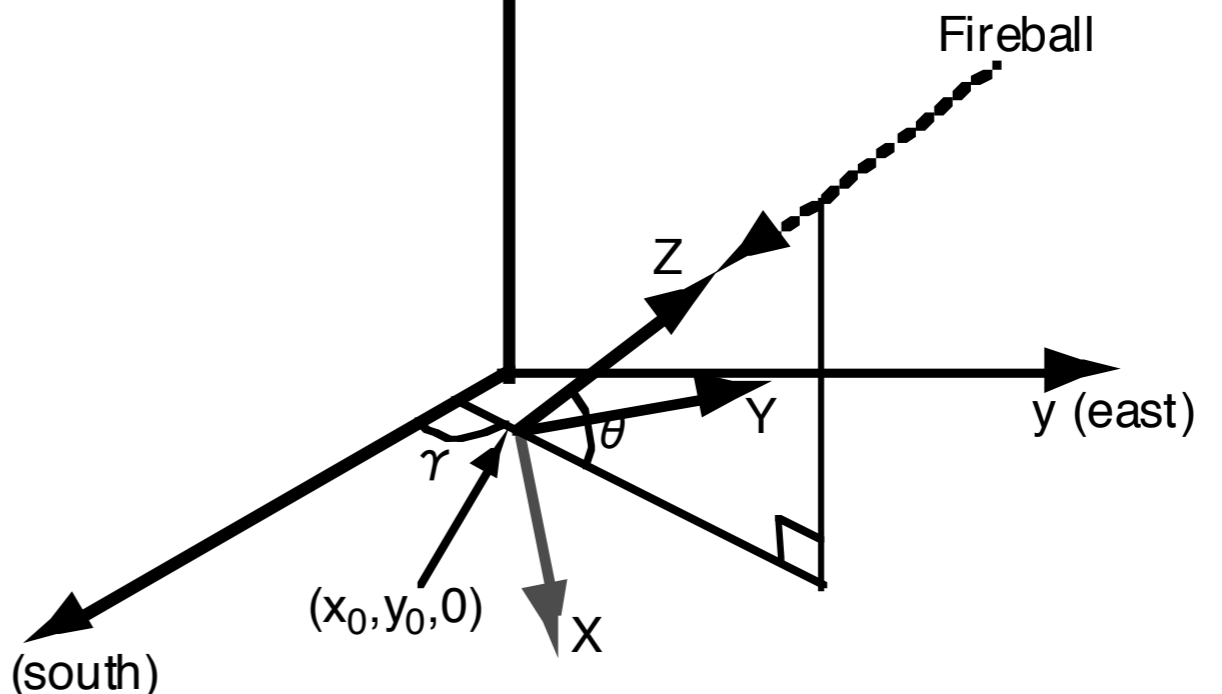
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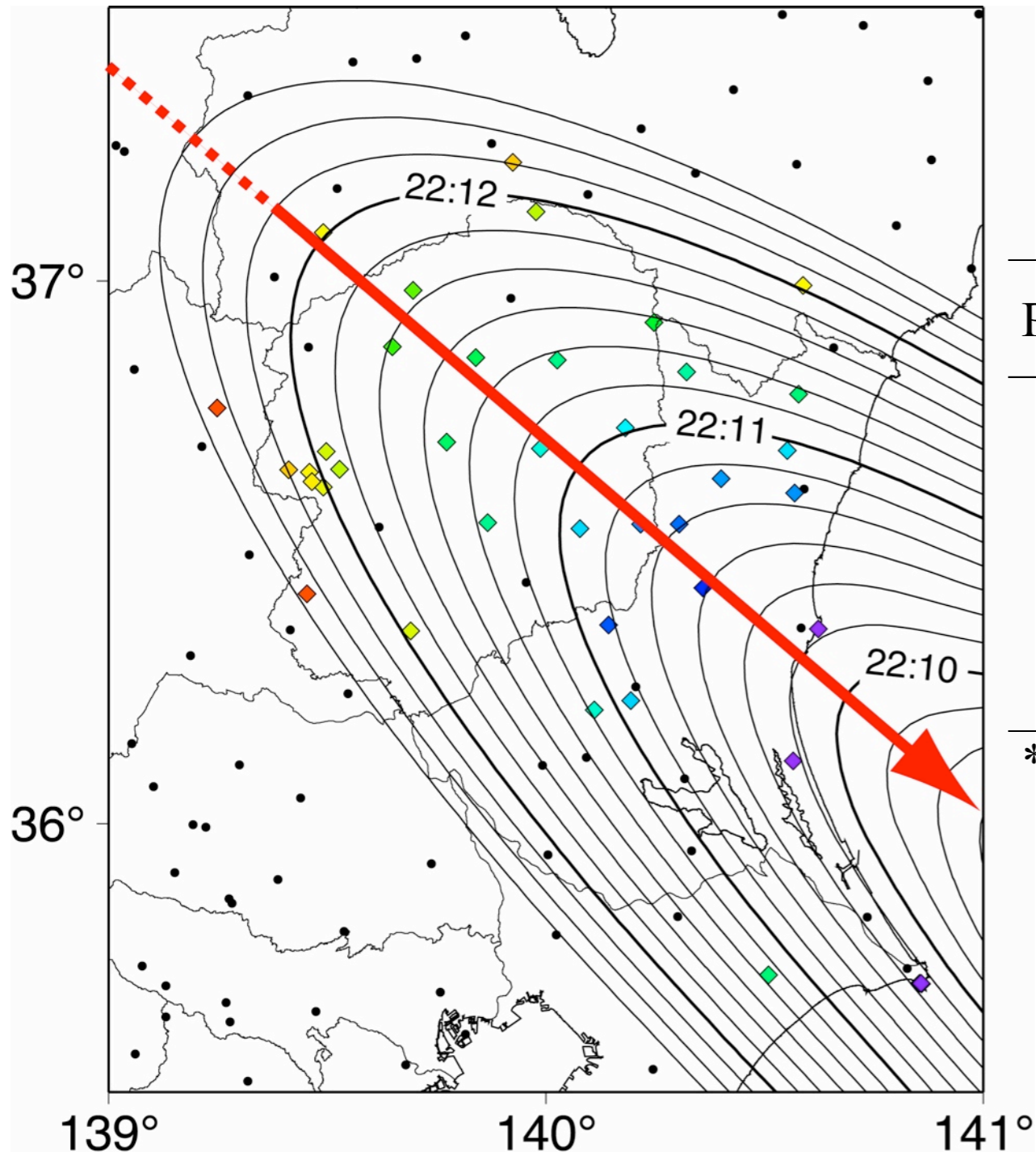
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Trajectory of 2003 Kanto Bolide



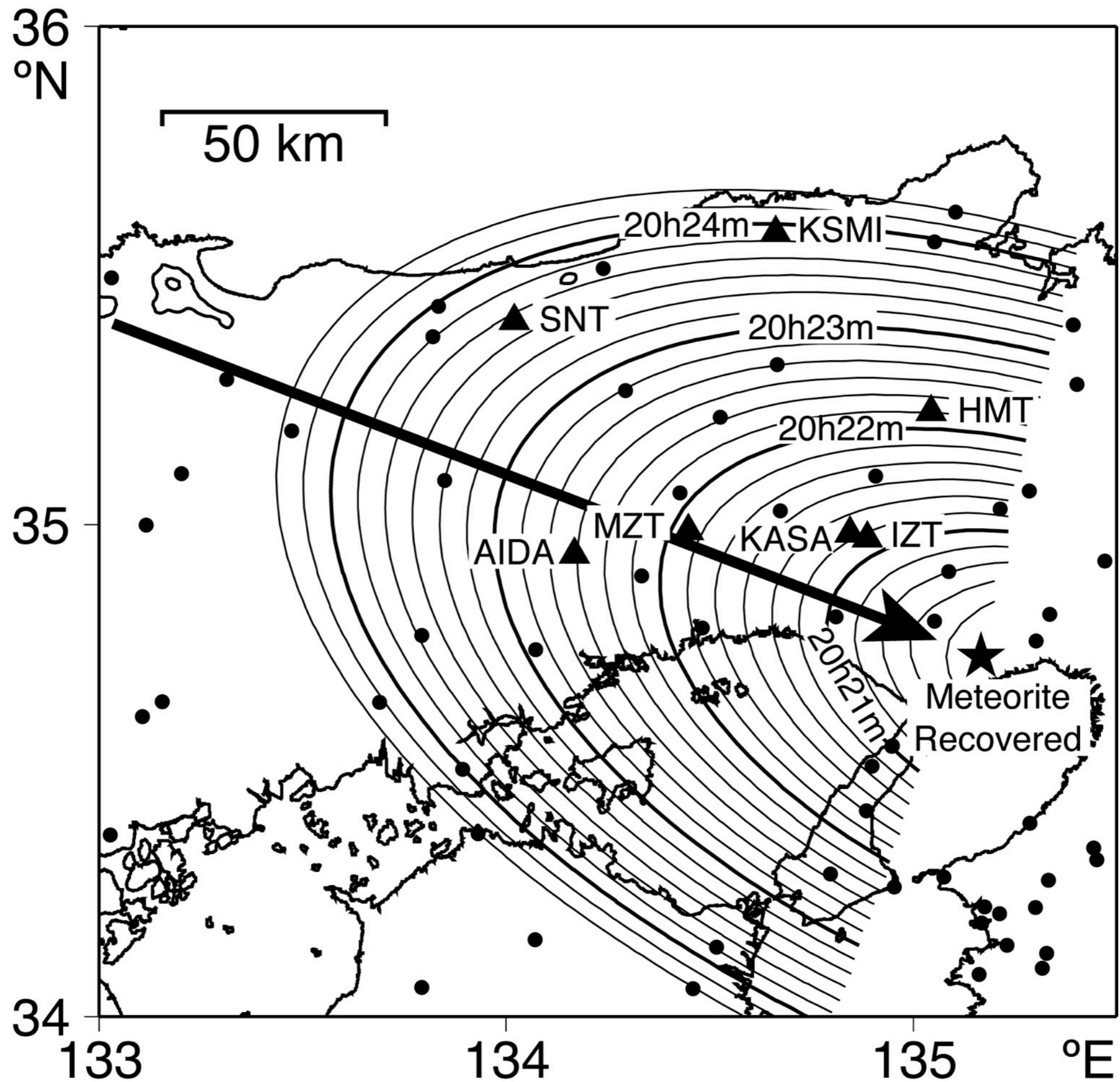
Parameter	Search Domain	Grid Interval	Optimum Value and Confidence Interval
v [km/s]	11 ~ 30	1.0	14.0 +10/-3
x_0 [km]	0 ~ 180	1.0	80 +7/-7
y_0 [km]	0 ~ 150	1.0	99 +6/-7
γ [°]	210 ~ 250	0.5	229.5 +1.5/-1.5
θ [°]	10 ~ 30	0.5	15.5 +1.0/-1.0
t_0 [s]	0 ~ 100	1.0	68 +8/-8

*The origin is (36 °N, 141°E, 0) at 22h06m40s JST.



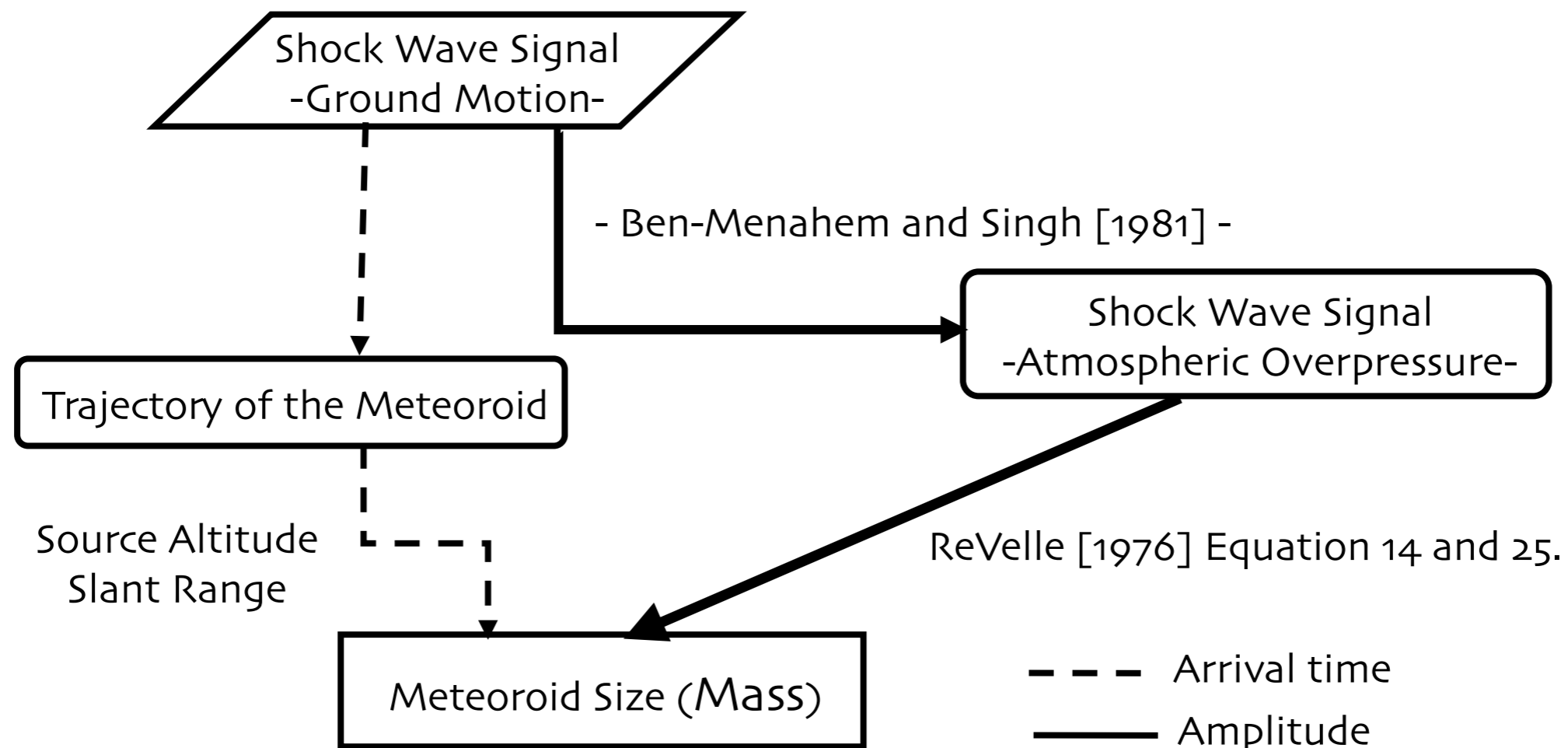
神戸隕石

- 日時：1999年9月26日 20時22分頃
- 落下地点: 兵庫県神戸市北区
- 隕石種: CK-4 (Tomeoka et al., 2000)
- 回収質量: 136 g
- 未回収分を含めるともう少しありそう？
- 地震観測点7点で衝撃波シグナルを検出



Meteoroid Size Estimation Using Seismic Data

Work Flow



Ground Motion Amplitude to Shockwave Overpressure

$$\Delta p = \frac{2\omega(\lambda + \mu)}{-\hat{C}} \left(\frac{\mu}{\lambda + \mu} \right) u_z$$

-Ben-Menahem and Singh [1981]-

Δp ...shock wave overpressure at the station [Pa]

ω ...angular frequency of ground motion [rad/s]

μ ...first Lamé's parameter of the station

λ ...second Lamé's parameter of the station

u_z ...vertical ground displacement [m]

\hat{C} ...apparent velocity of the shock wave [m/s]

$$\mu = \rho v_s^2$$
$$\lambda = \rho(v_p^2 - 2v_s^2)$$

Shockwave Overpressure to Meteoroid Size

$$R_o \approx M \cdot d_m$$

R_o ...conical shock wave relaxation radius [m]

M ...Mach number of meteoroid

d_m ...meteoroid diameter [m]

- ReVelle [1976] Equation 14 -

$$\frac{\Delta p}{p_0} = \frac{2\gamma}{\gamma + 1} \left(\frac{0.4503}{(1 + 4.803x^2)^{3/8} - 1} \right) \left(\frac{p_z}{p_0} \right)^{1/2}$$

- ReVelle [1976] Equation 25 -

$$x = R / R_o$$

Δp ...shock wave overpressure at station [Pa]

p_0 ...hydrostatic pressure at station [Pa]

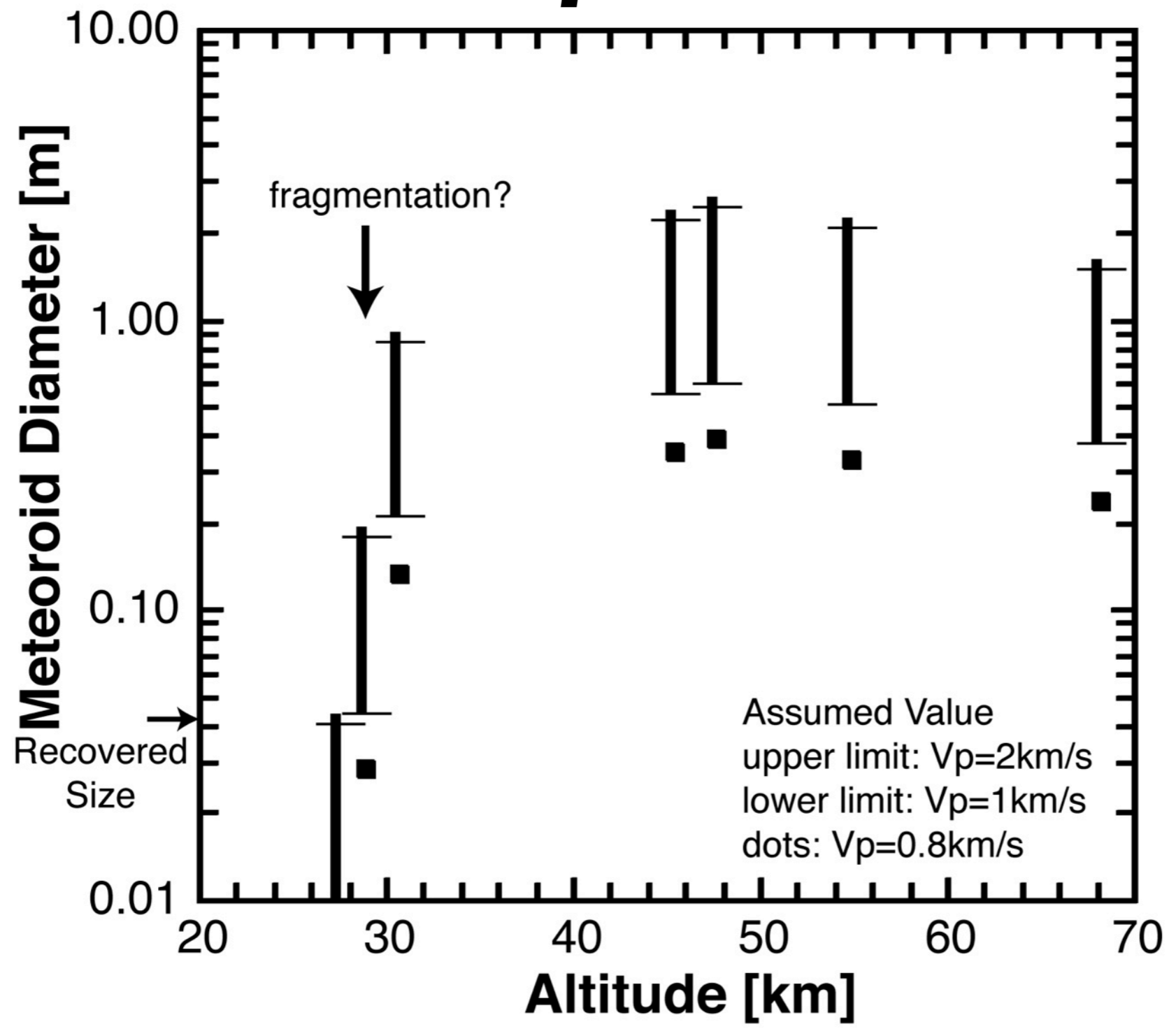
p_z ...hydrostatic pressure at source altitude [Pa]

γ ...the ratio of the specific heat of air at constant pressure to that at constant volume (=1.4)

R ...radial distance from the source [m]

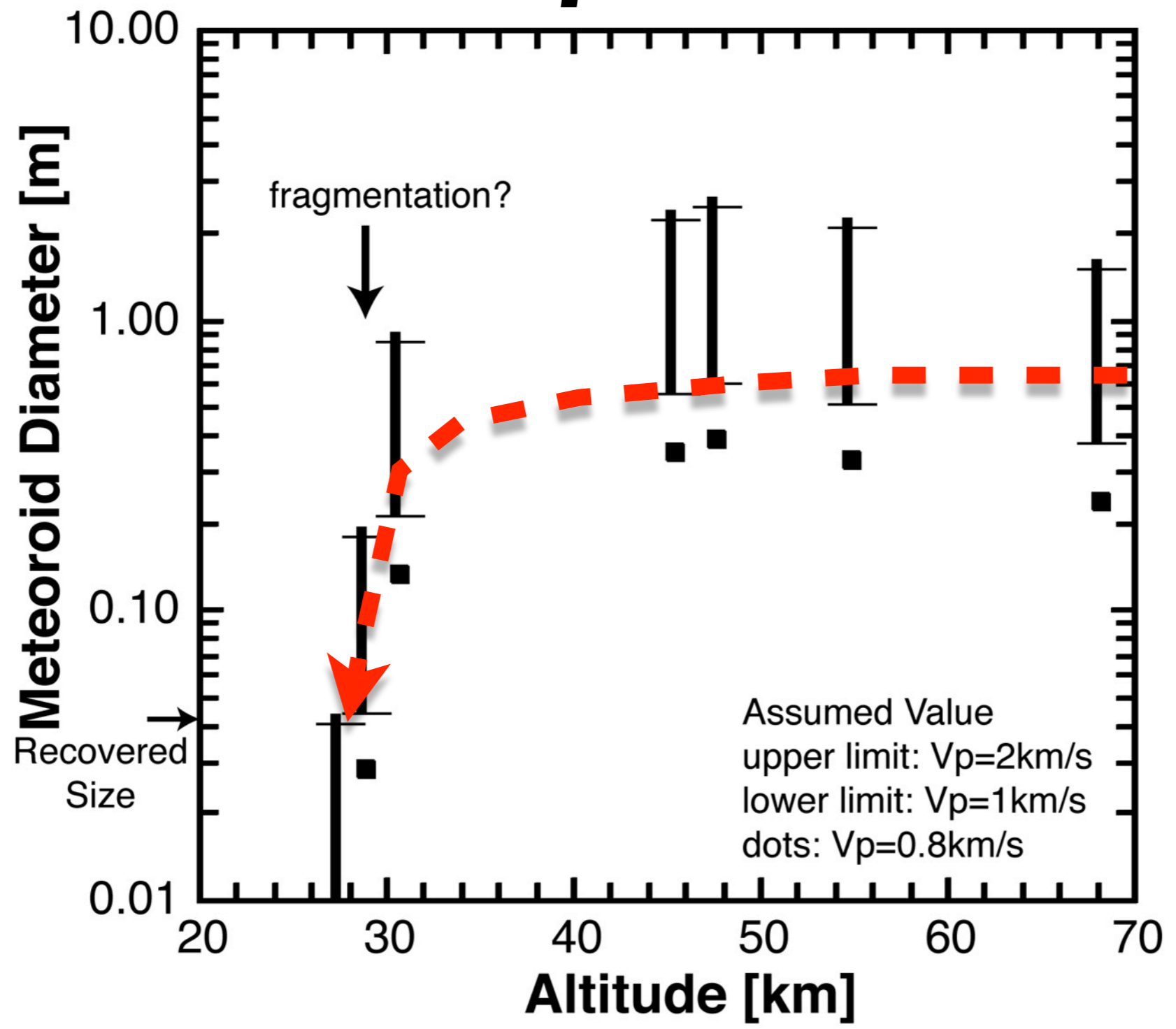
R_o ...conical shock wave relaxation radius [m]

Seismical Estimation of Ablation / Fragmentation / Size of Meteoroid



[Ishihara, 2004, Ph.D. thesis @ Kanazawa Univ.]

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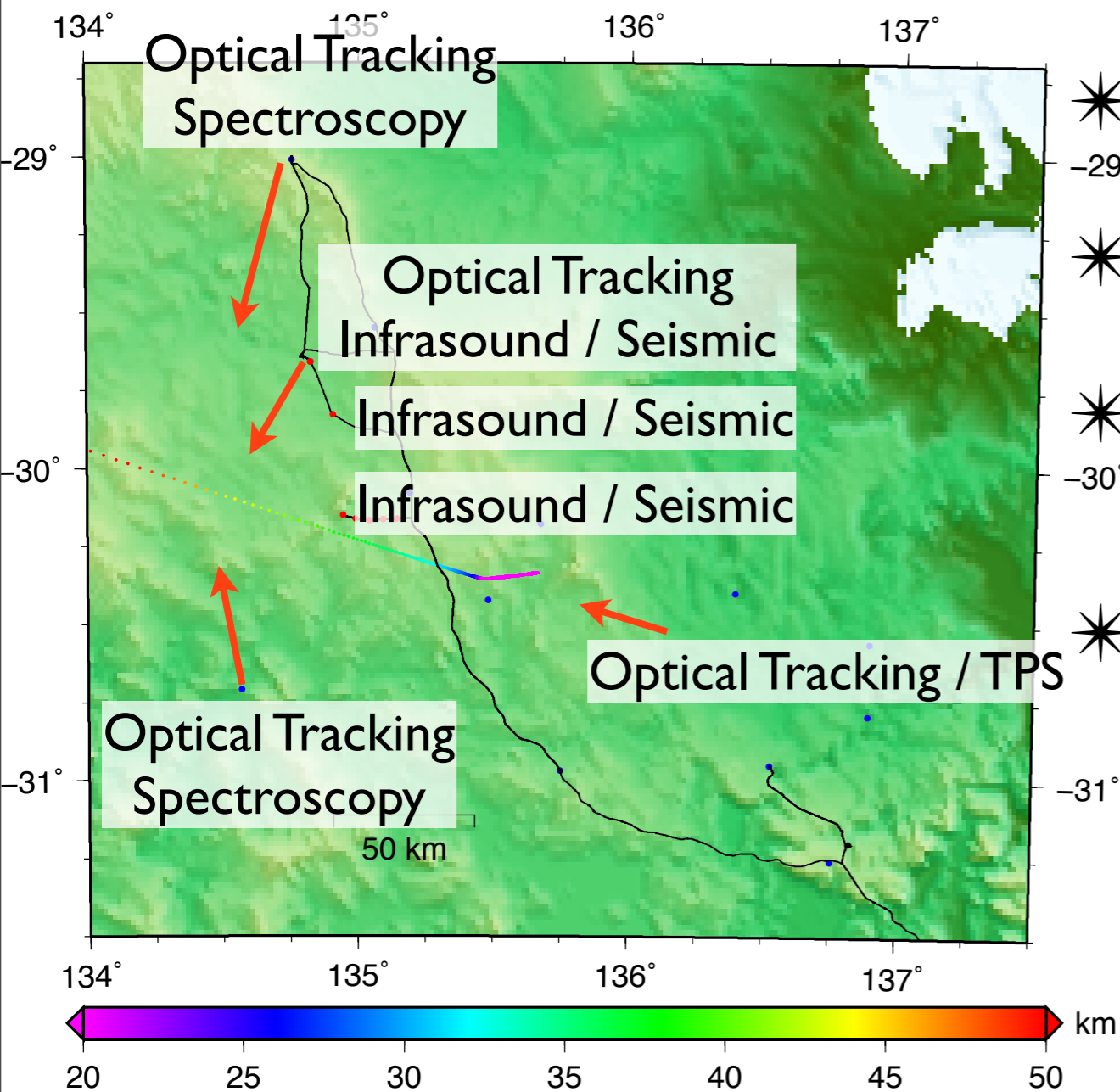
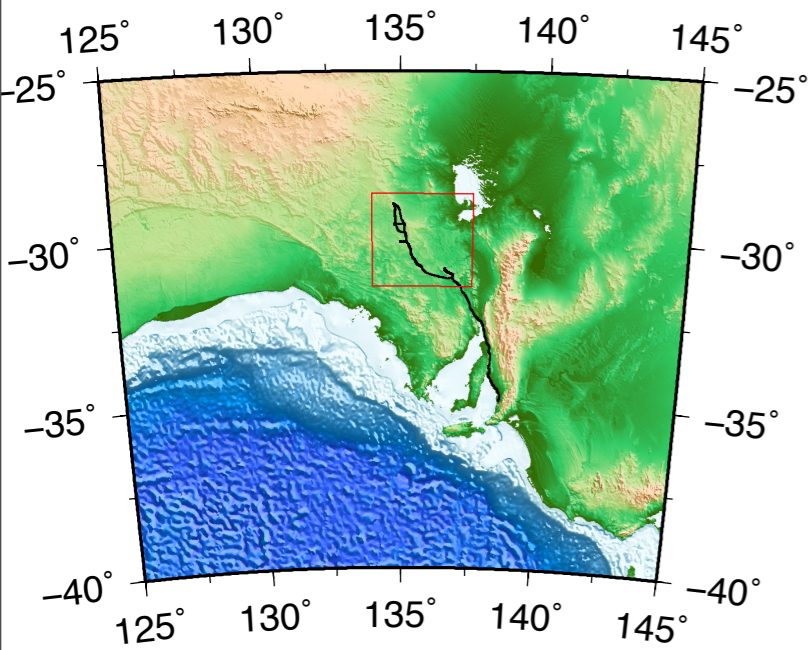
Parameters of HAYABUSA Reentry

- Date and Time: June 13, 2010 / 14:00 UT
- Location: Woomera Prohibited Area @ Australia
- V_{int} : ~ 12 km/s
- Size: 40 cm (capsule)
- Material: Carbon Phenolic (heat shield)

Parameters of HAYABUSA Reentry

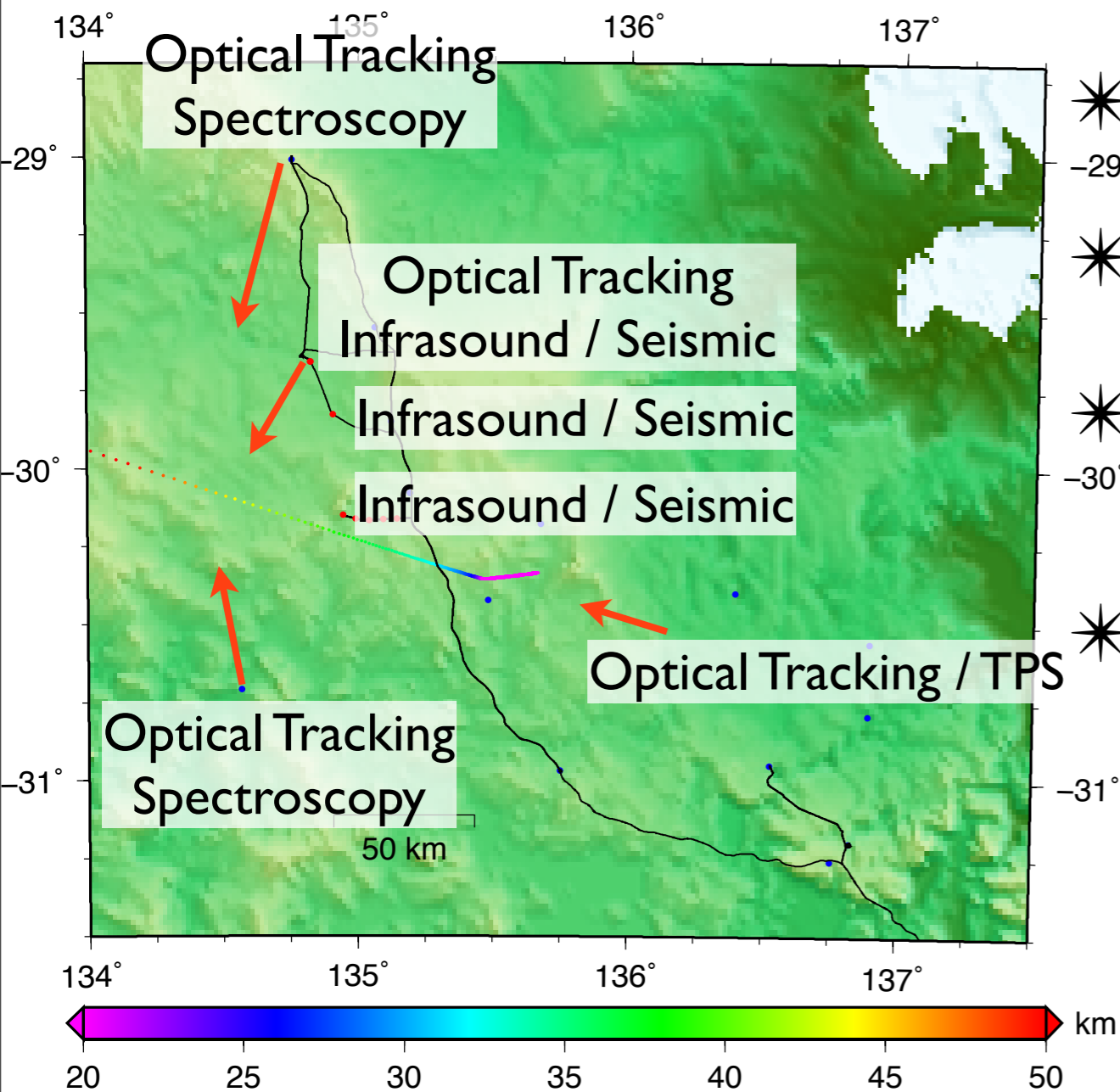
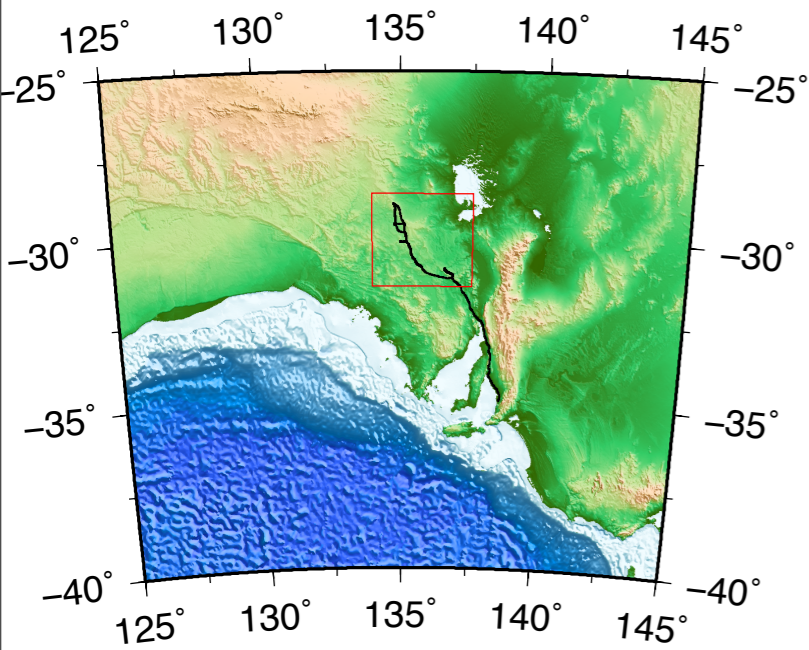
- Date and Time: June 13, 2010 / 14:00 UT
- Location: Woomera Prohibited Area, Australia
- **This is the third artificial meteorite fall !!**
- Size: 40 cm (capsule)
- Material: Carbon Phenolic (heat shield)

GOS Observations



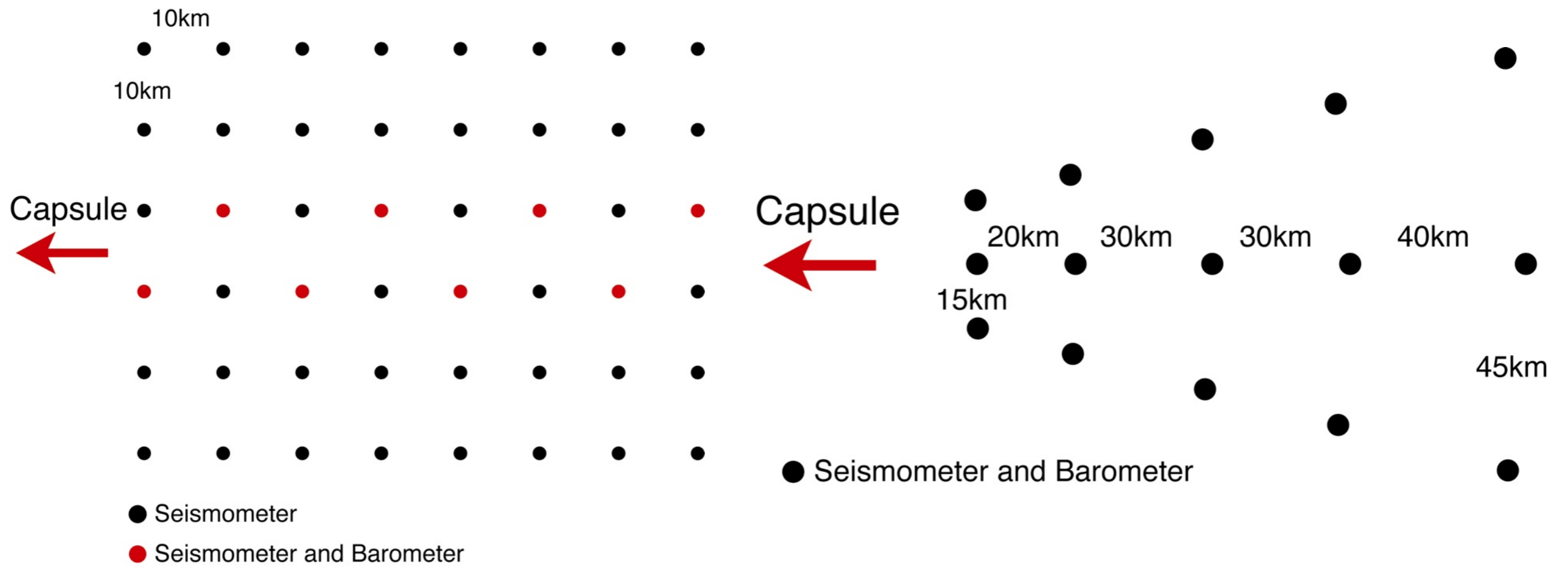
- * **Optical Tracking**
 - Determination of Trajectory
- * **TPS Science**
 - Measurement of the Heating History of TPS
- * **Spectroscopy**
 - Determination of What Elements Emit Light in the Meteor Head and Wake.
- * **Infrasonic / Seismic**
 - Detection of Shockwaves Generated by Hypersonic Flight of Capsule and S/C.
 - Detection of Shockwaves Generated by Energetic Fragmentations of S/C.

GOS Observations



- * **Optical Tracking**
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Previous Plan...



Plan-1

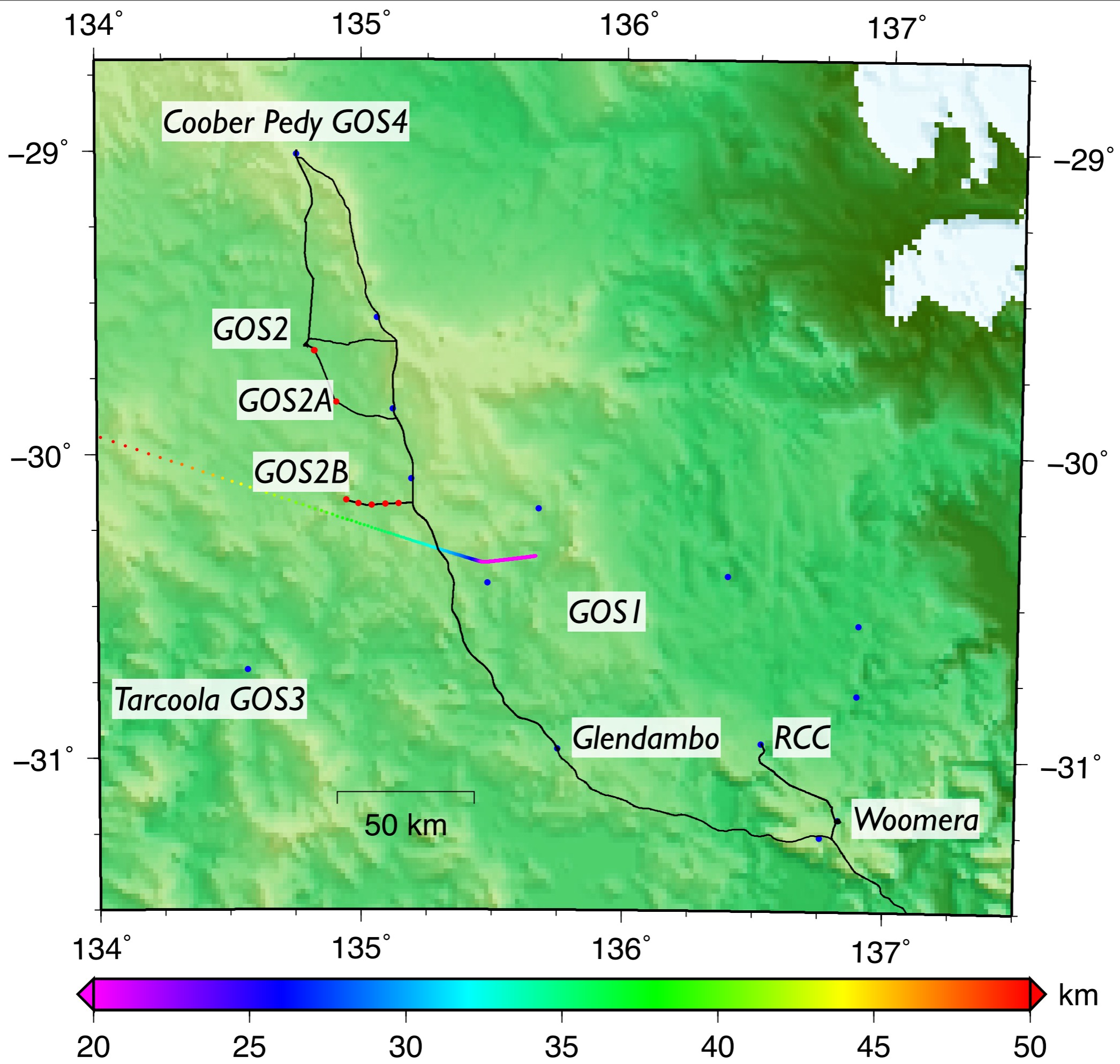
Plan-2

Previous Plan...



Infrasound / Seismic Instruments

- Chaparral Physics Model-2 ×2
- Chaparral Physics Model-25 ×3
- 4.5 Hz vertical velocity type seismometer x 20
- 4.5 Hz tri-axes velocity type seismometer × 2
- ✓ DATAMARK LS-7000
- ✓ DATAMARK LS-8200SD



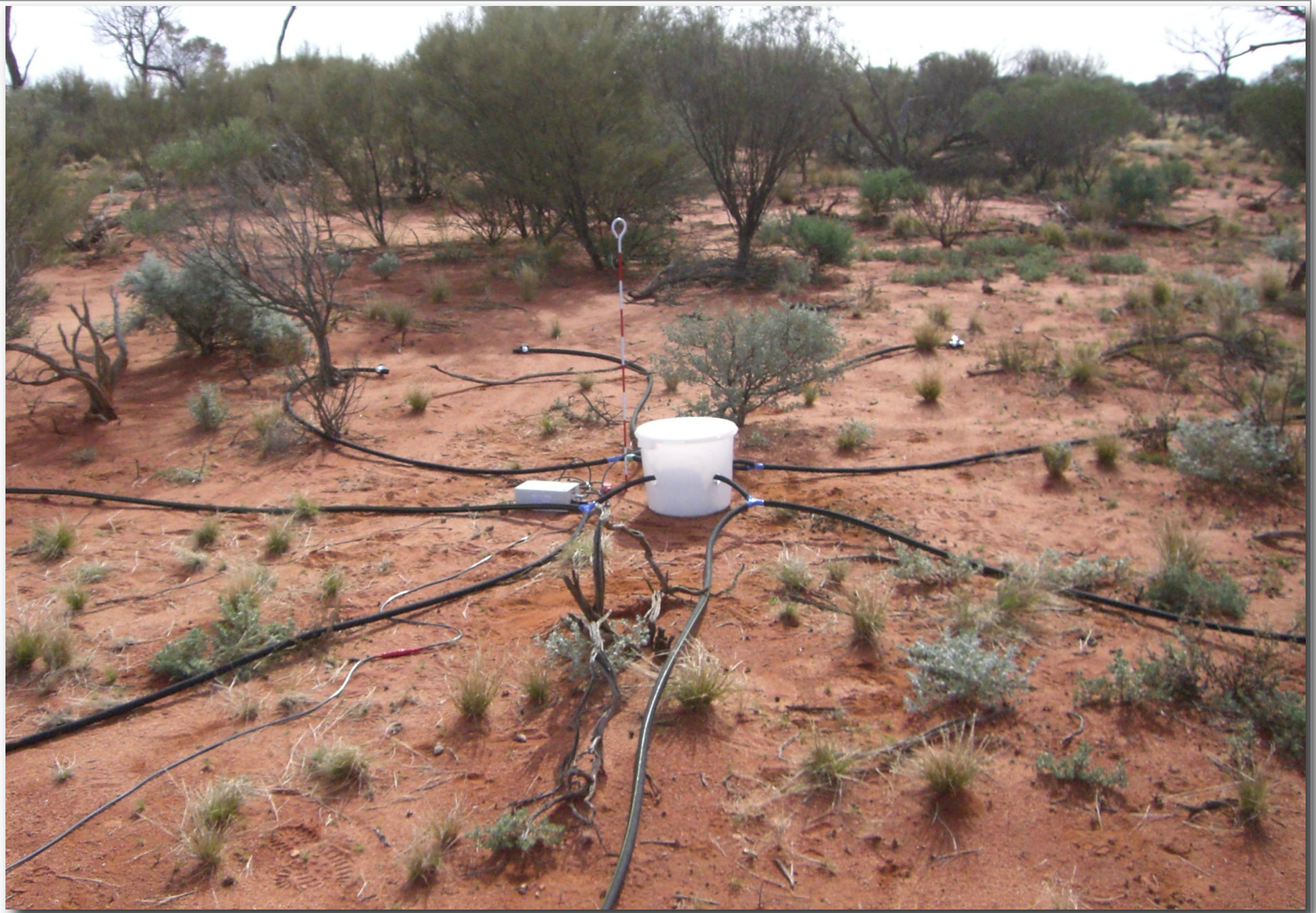






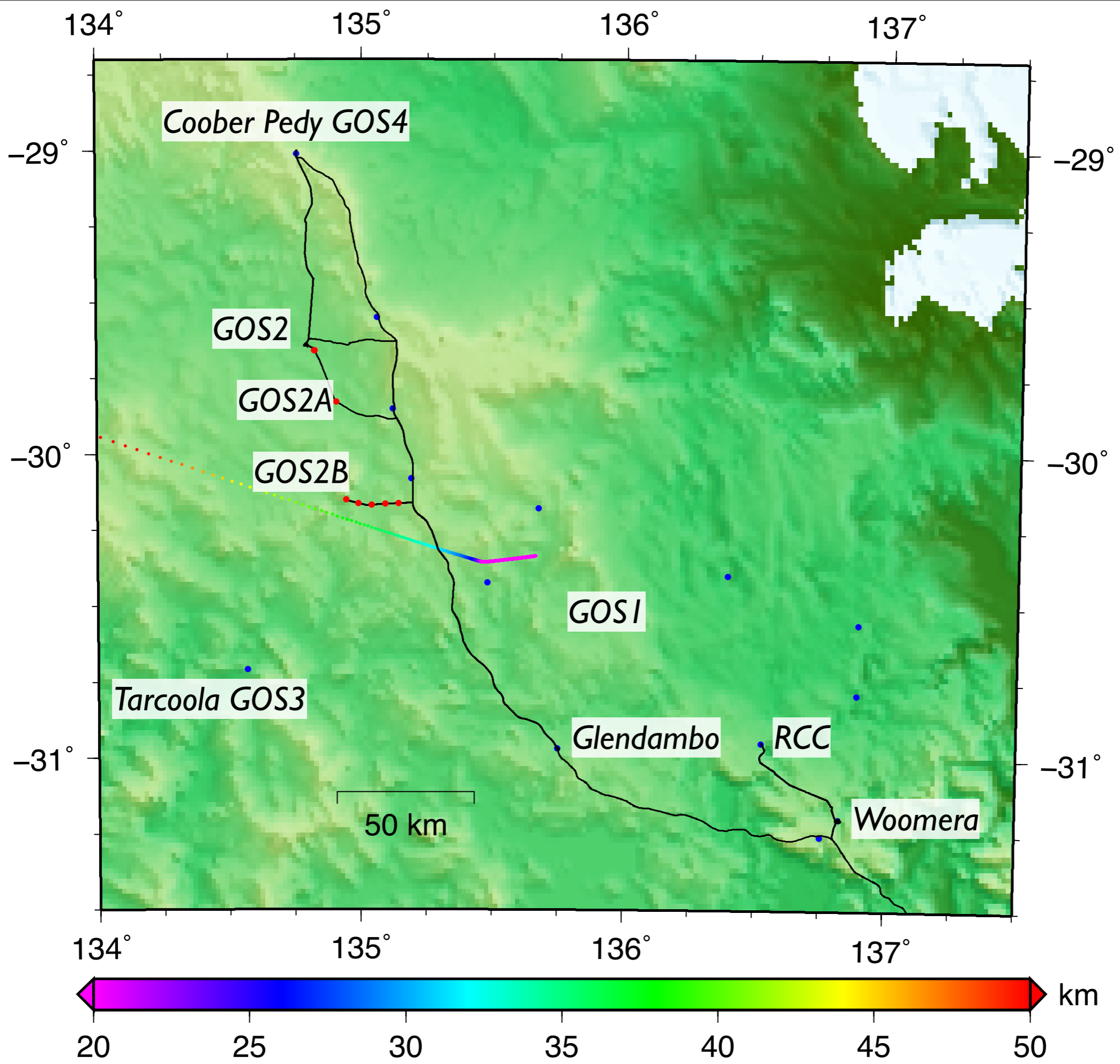




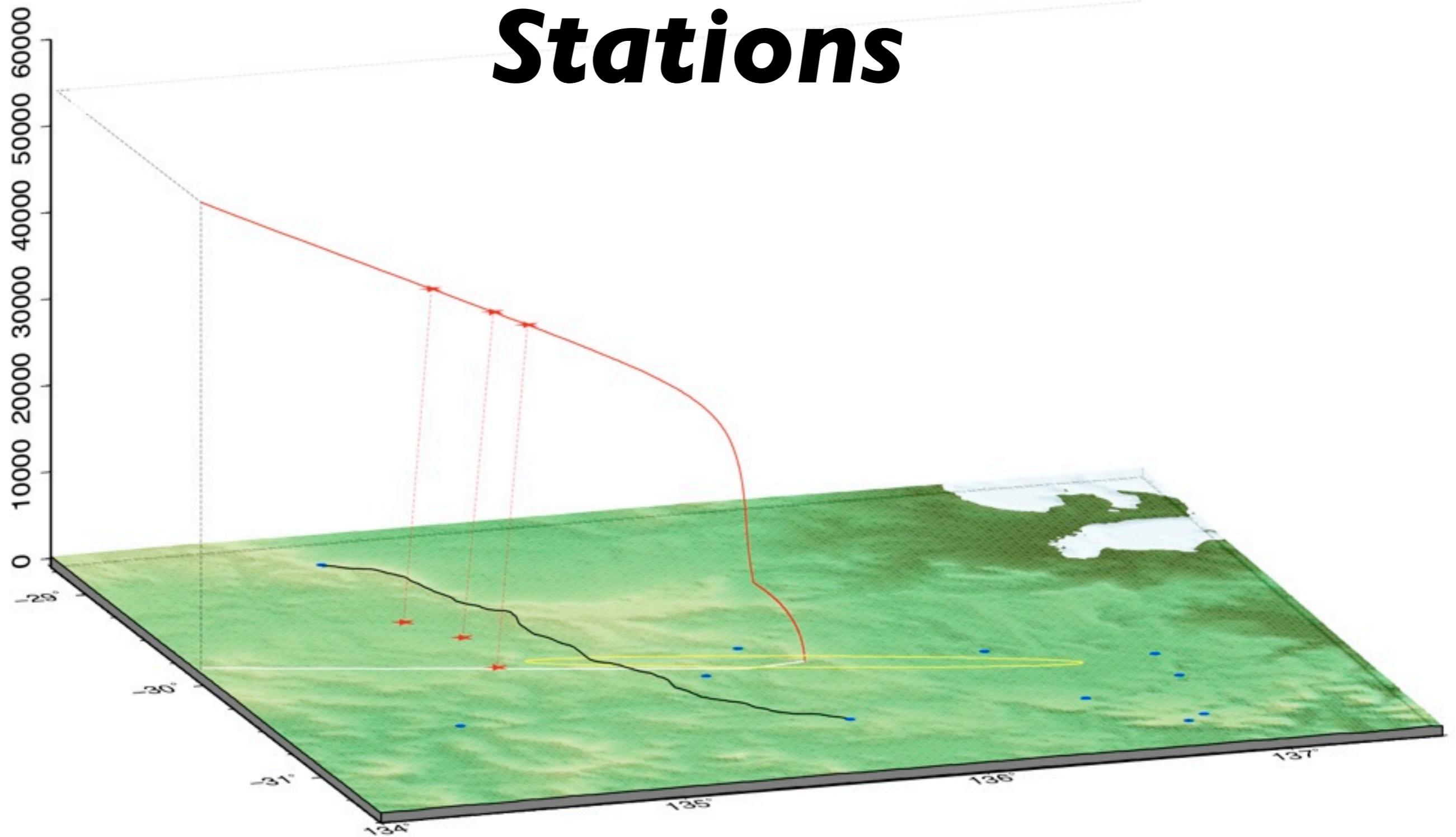




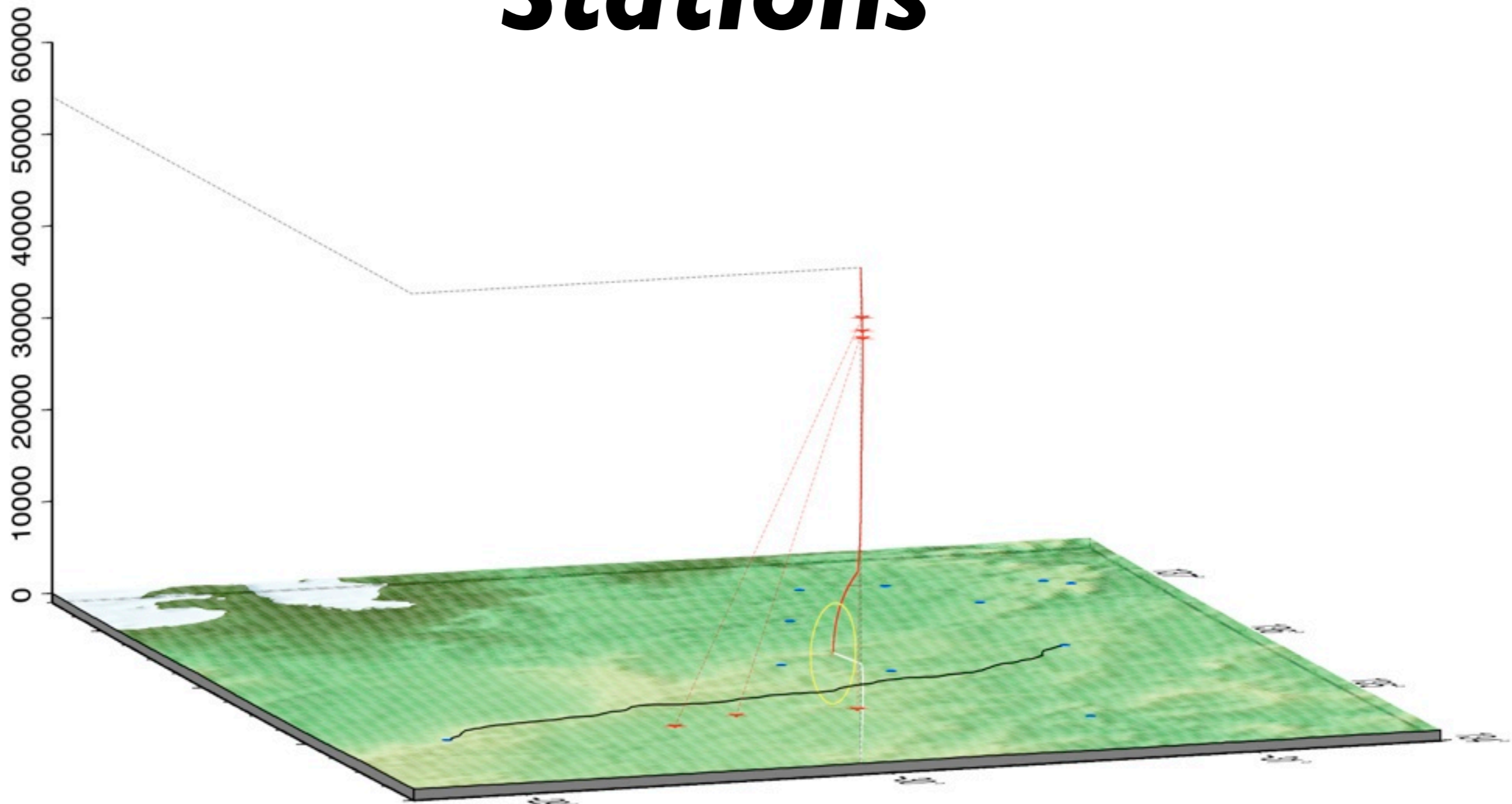




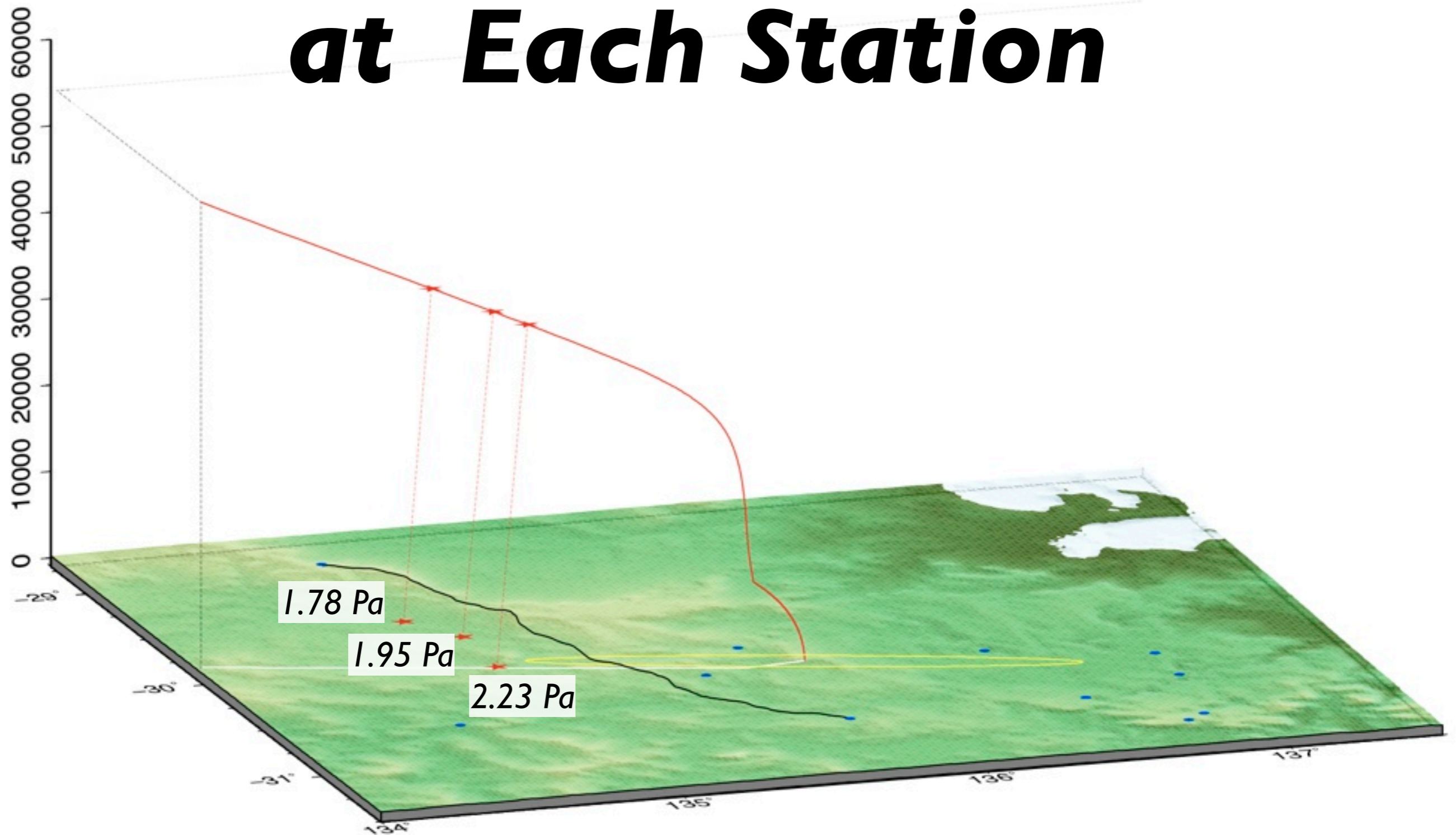
Location of Infrasound / Seismic Stations



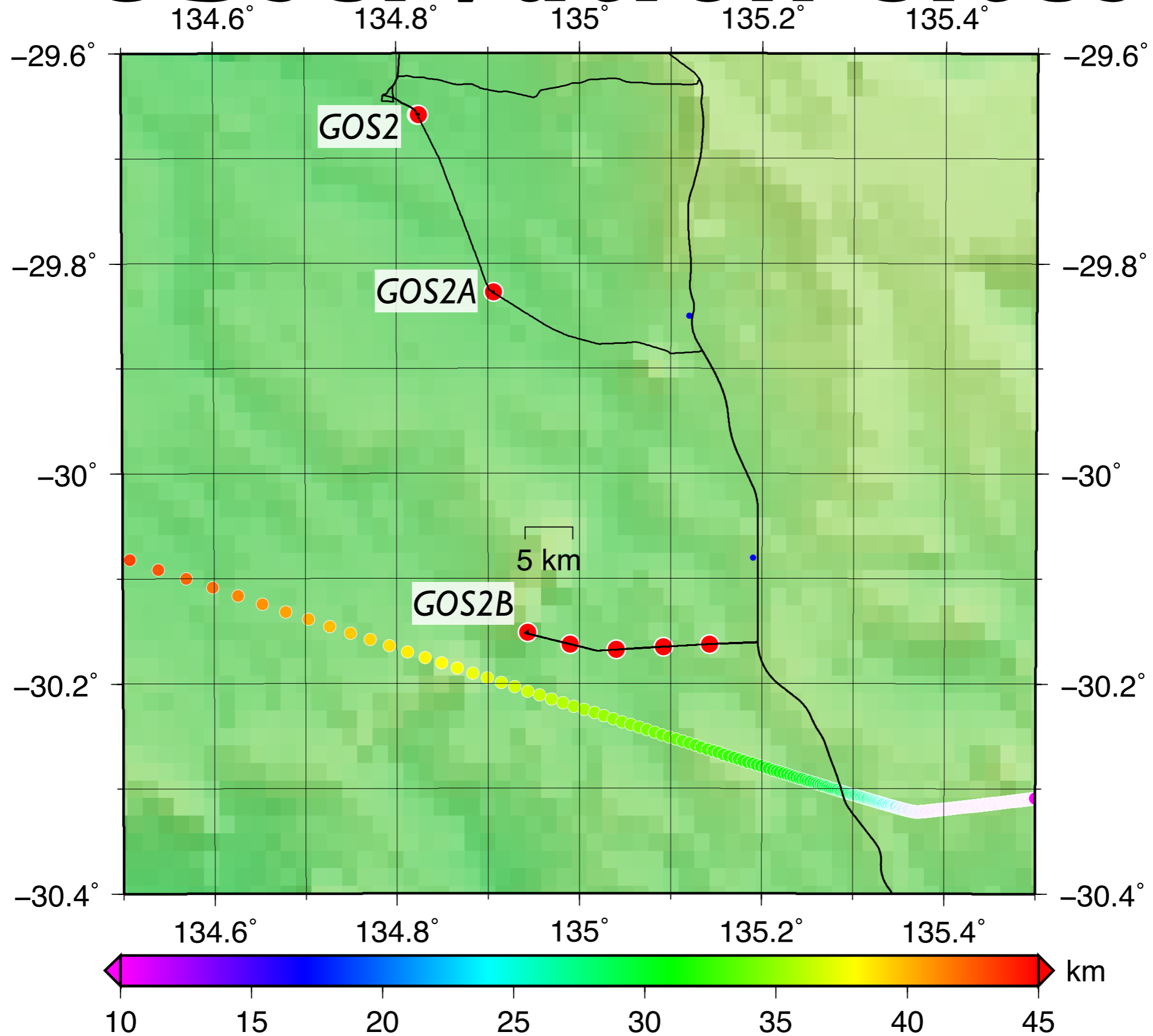
Location of Infrasound / Seismic Stations



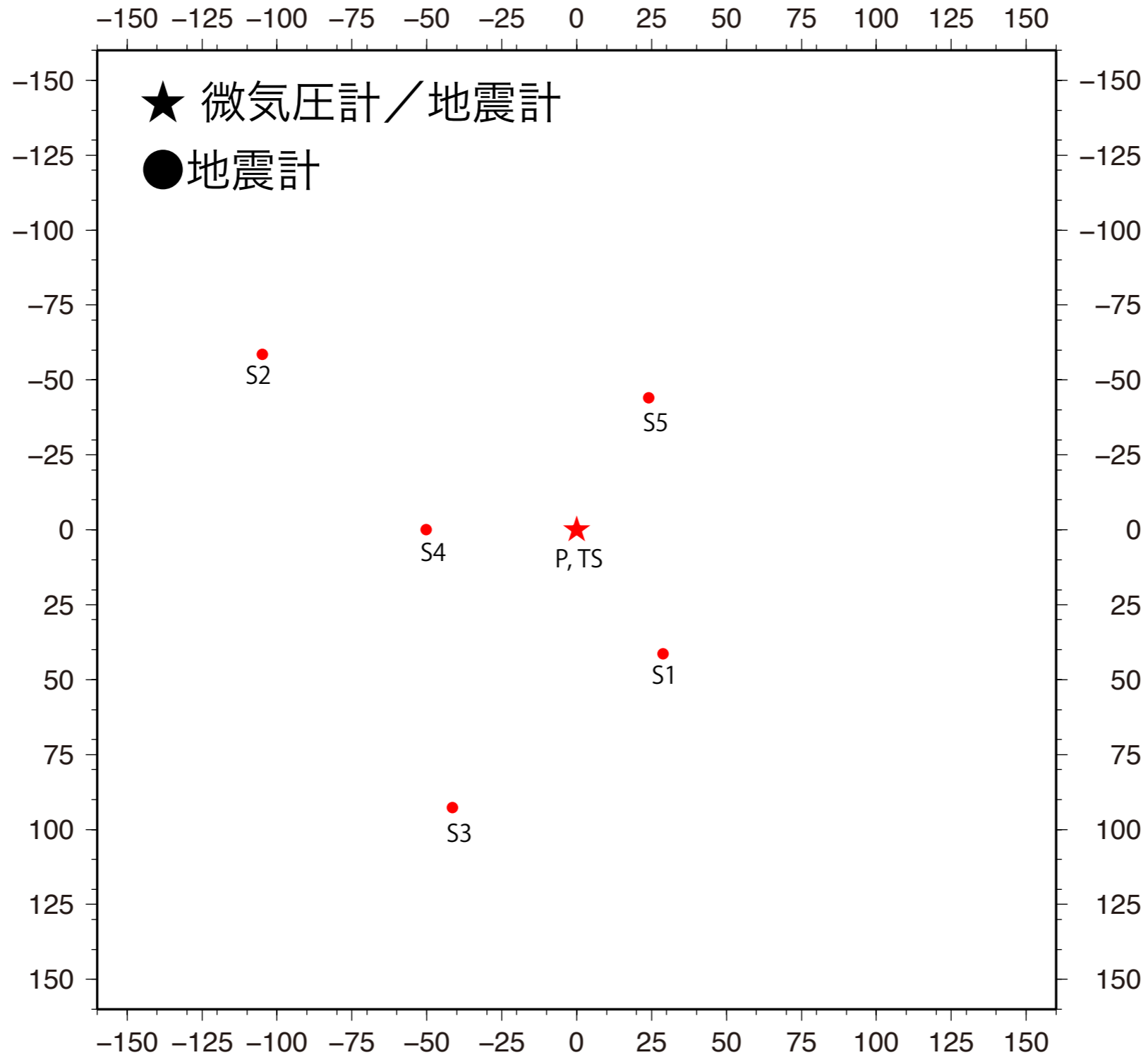
Rough Estimate of Infrasound Amplitude at Each Station



Observation Sites

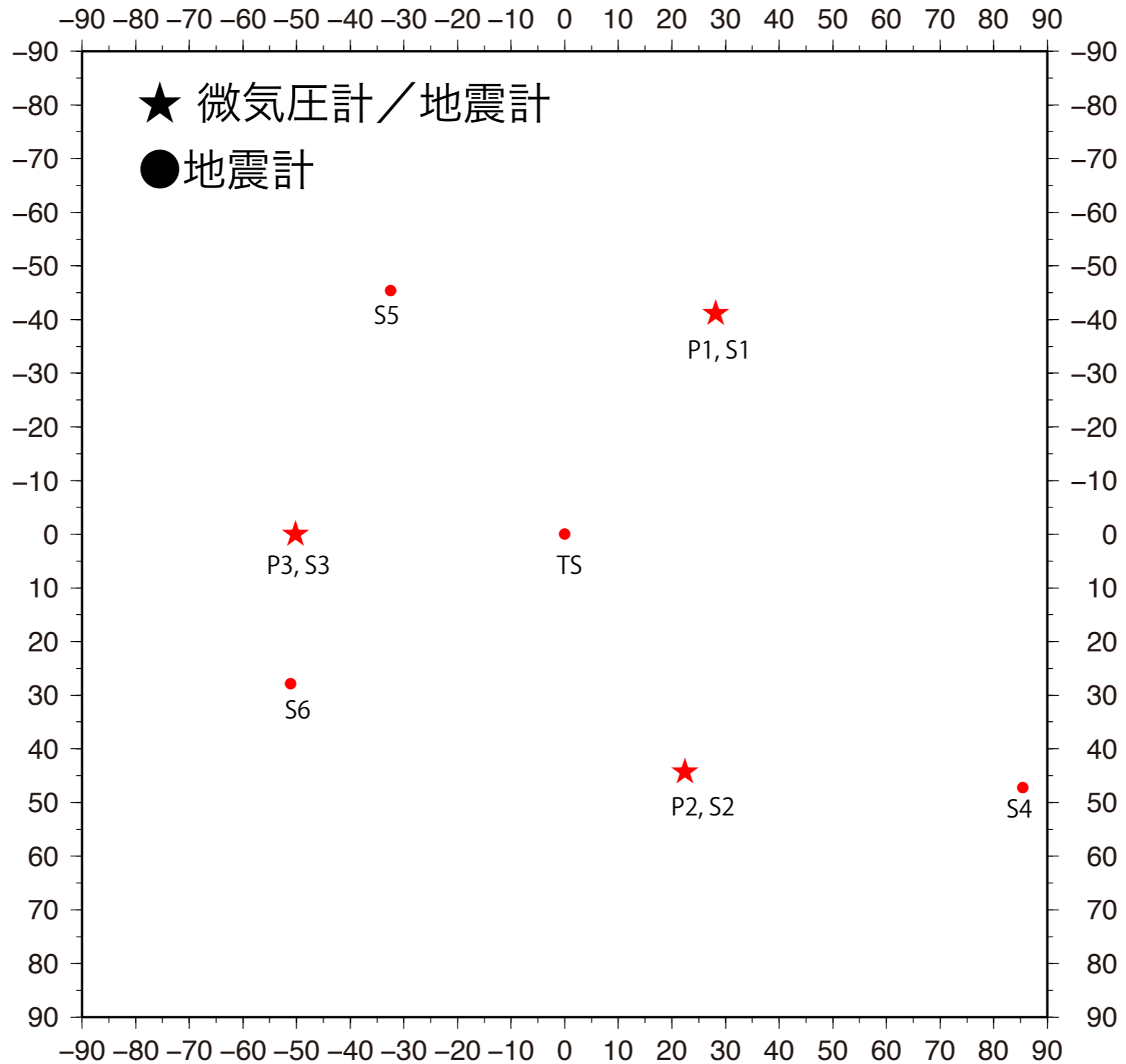


Infrasound-Seismic Array Observation (GOS2)



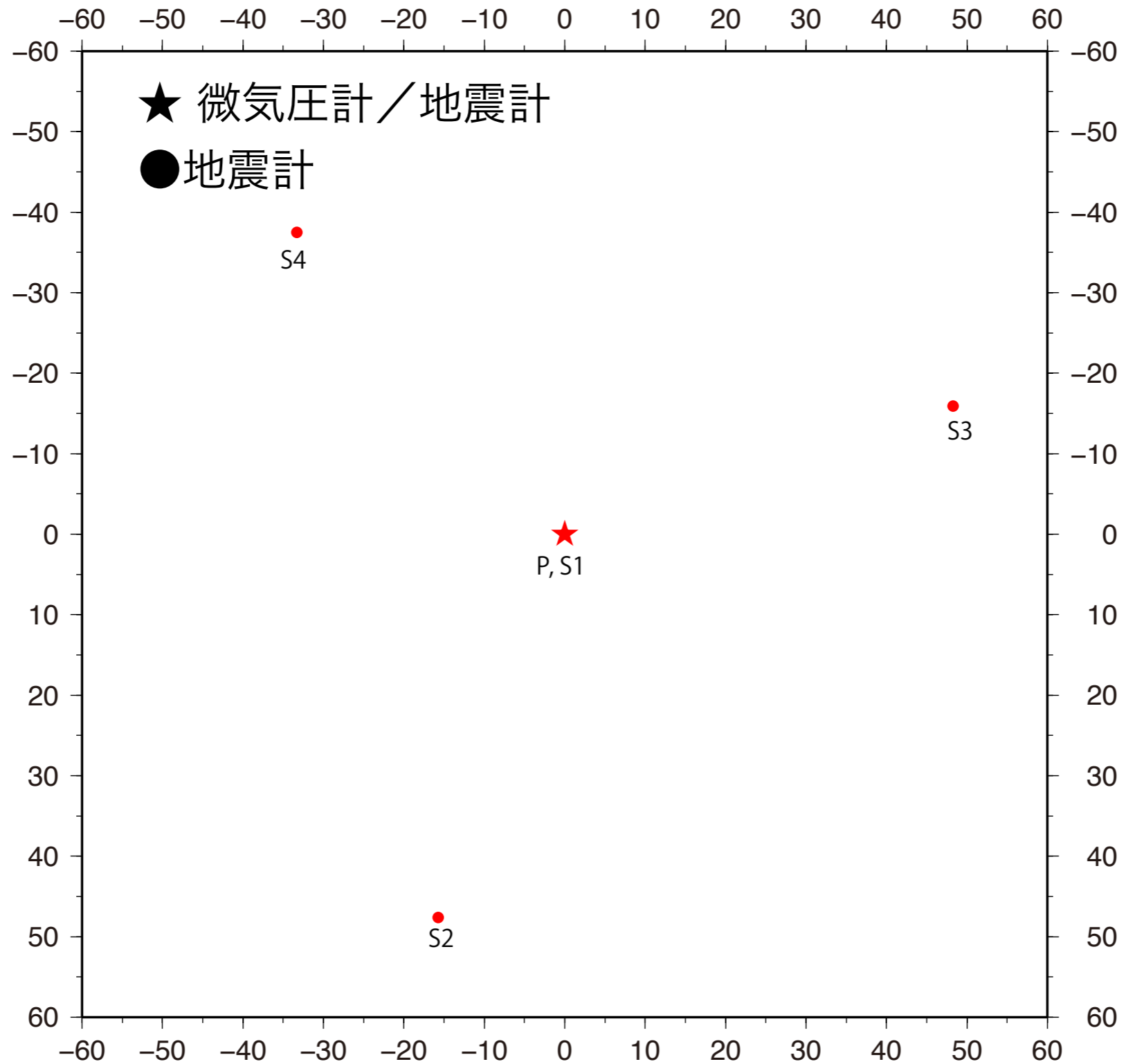
Array geometry will be measured using totalstation.

Infrasound-Seismic Array Observation (GOS2A)



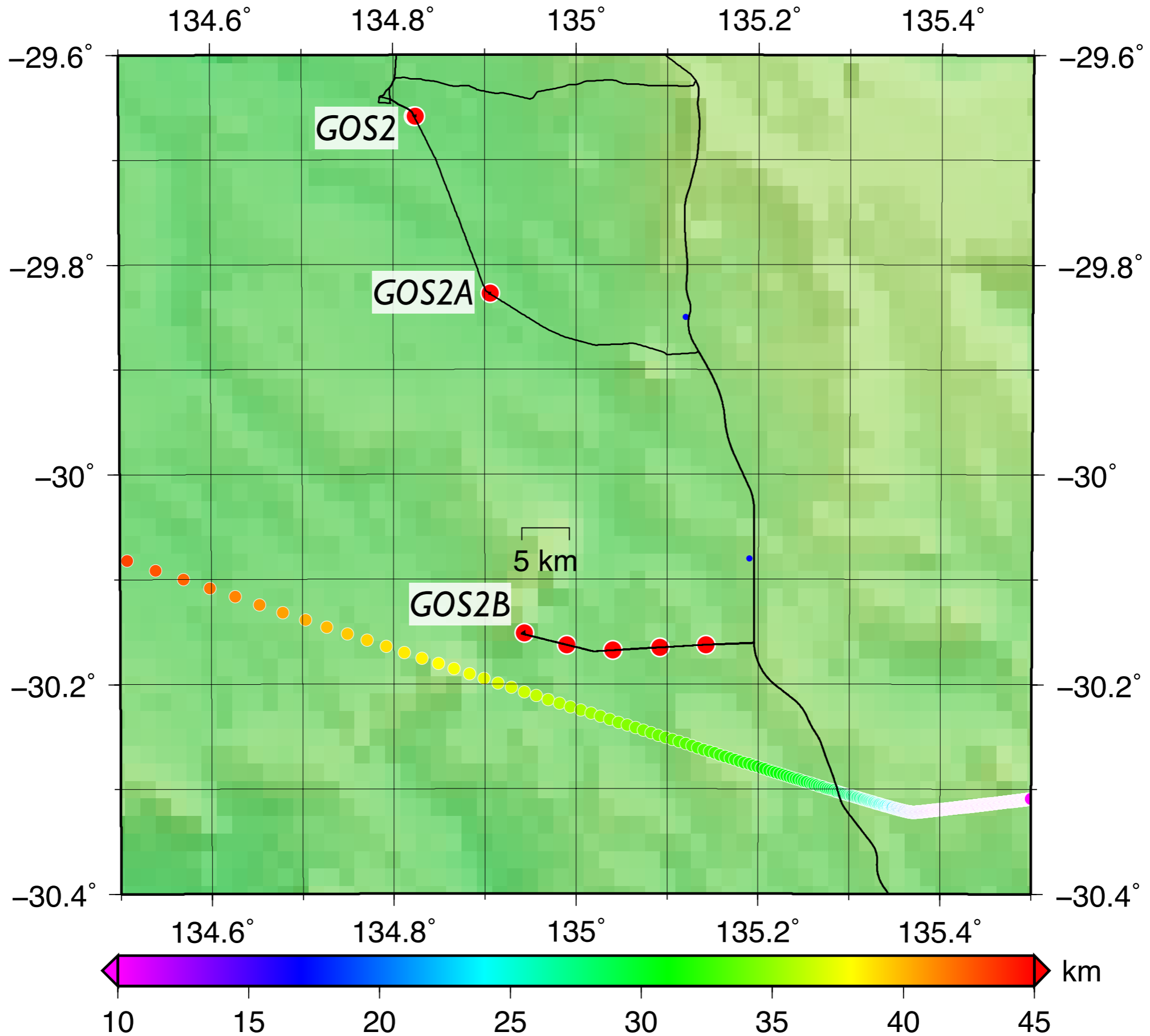
Array geometry will be measured using totalstation.

Infrasound-Seismic Array Observation (GOS2B)



Array geometry will be measured using totalstation.

Observation Sites



Why Array Observation?

- Easy & Robust Detection of Shockwave Signal(s).
- To Estimate Direction of Shockwave Arrival(s).
 - ➔ F-K Spectrum (Beam Forming / MUSIC)
 - ⊙ independent estimation by particle motion of tri-axes (vertical / n-s / e-w) seismogram
- To Estimate Elastic Parameters of Ground.
 - ➔ Seismic Interferometry
 - ➔ Array Analysis (e.g., SPAC)



野犬にズタズタにされたGOSアンテナケーブル

















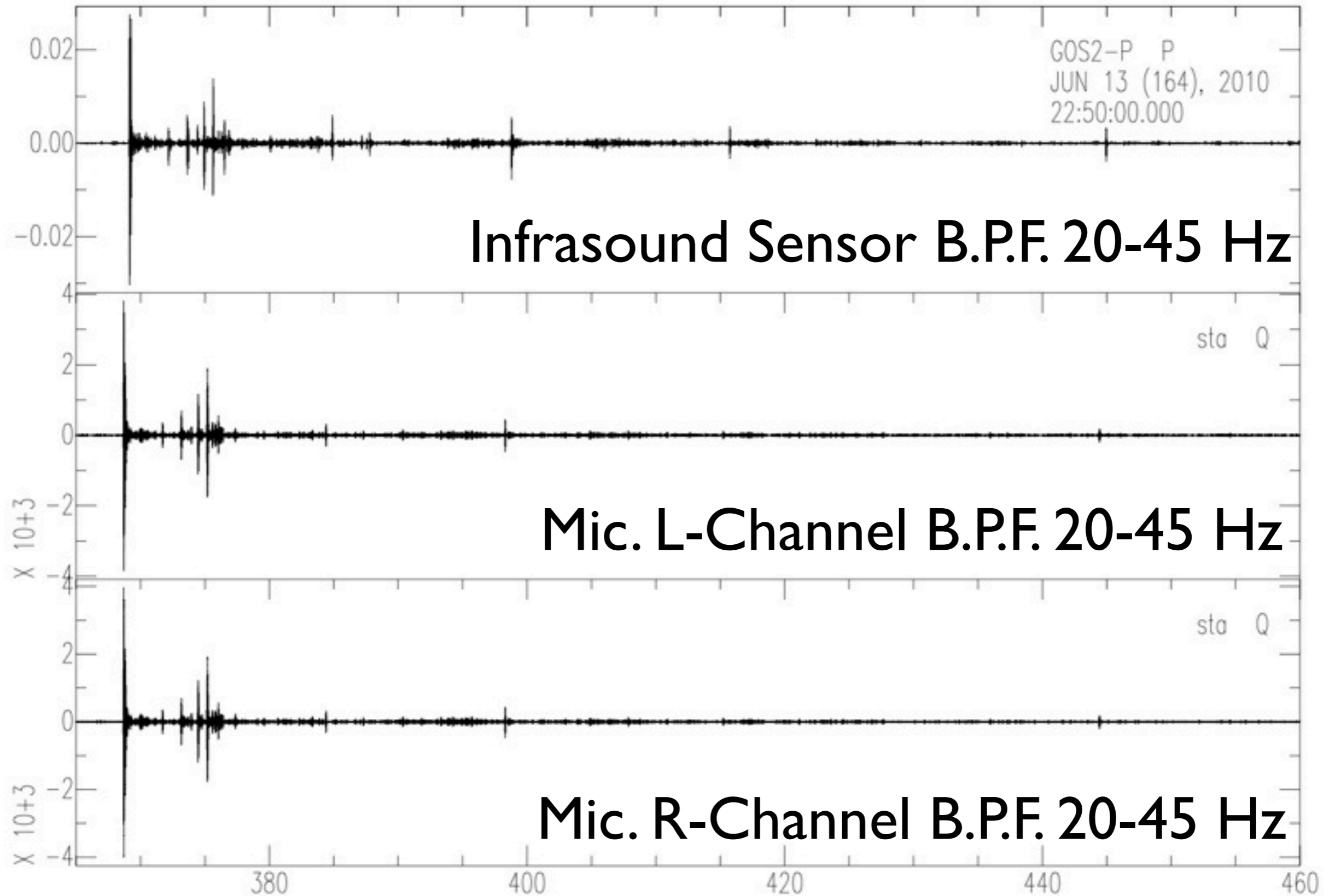




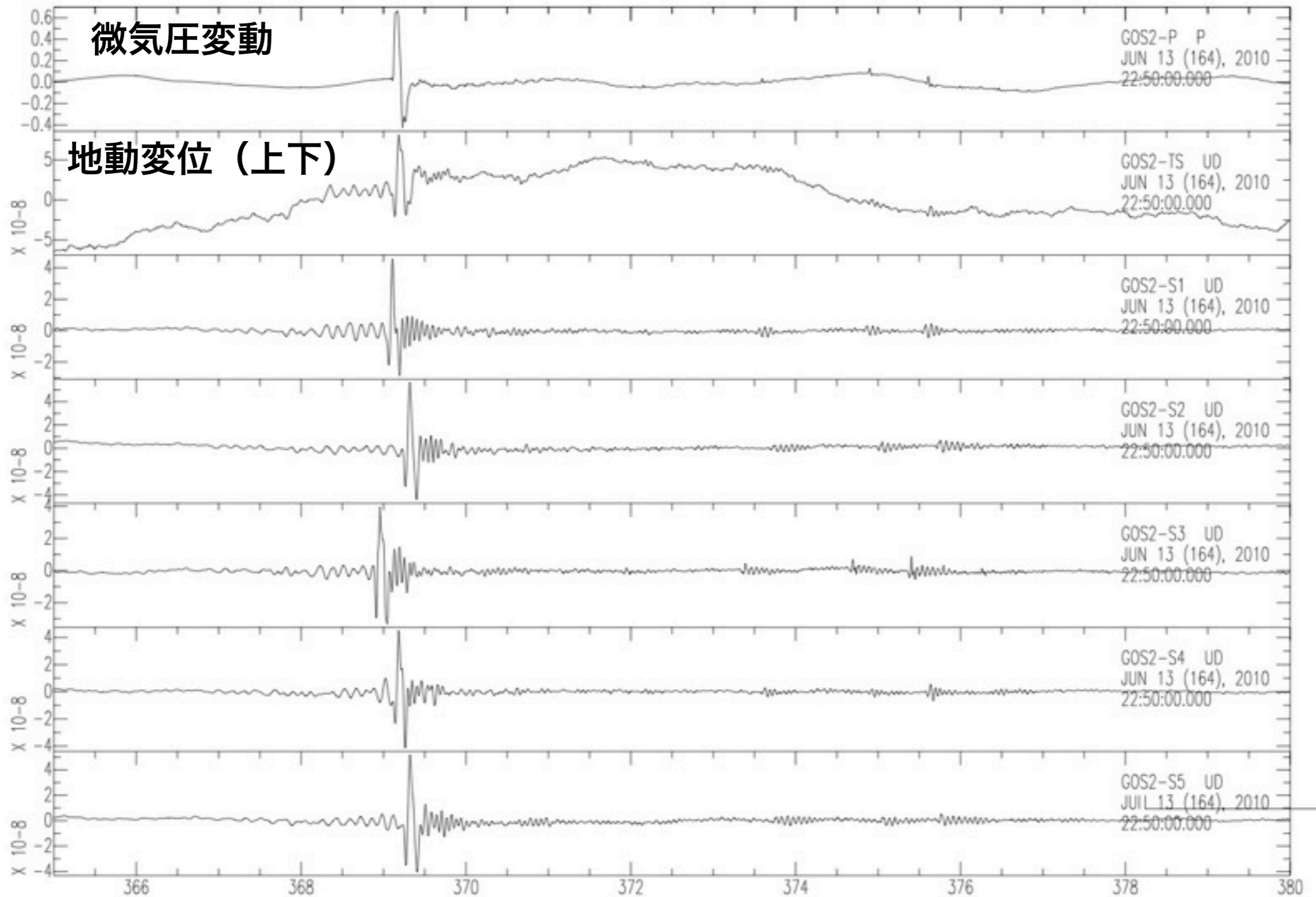
Obtained Data

- Photos
- Movies
- Spectrum
- Infrasound Signals at 3 stations
- Seismic Signals at 6 stations
- Audible Sound Signals !!

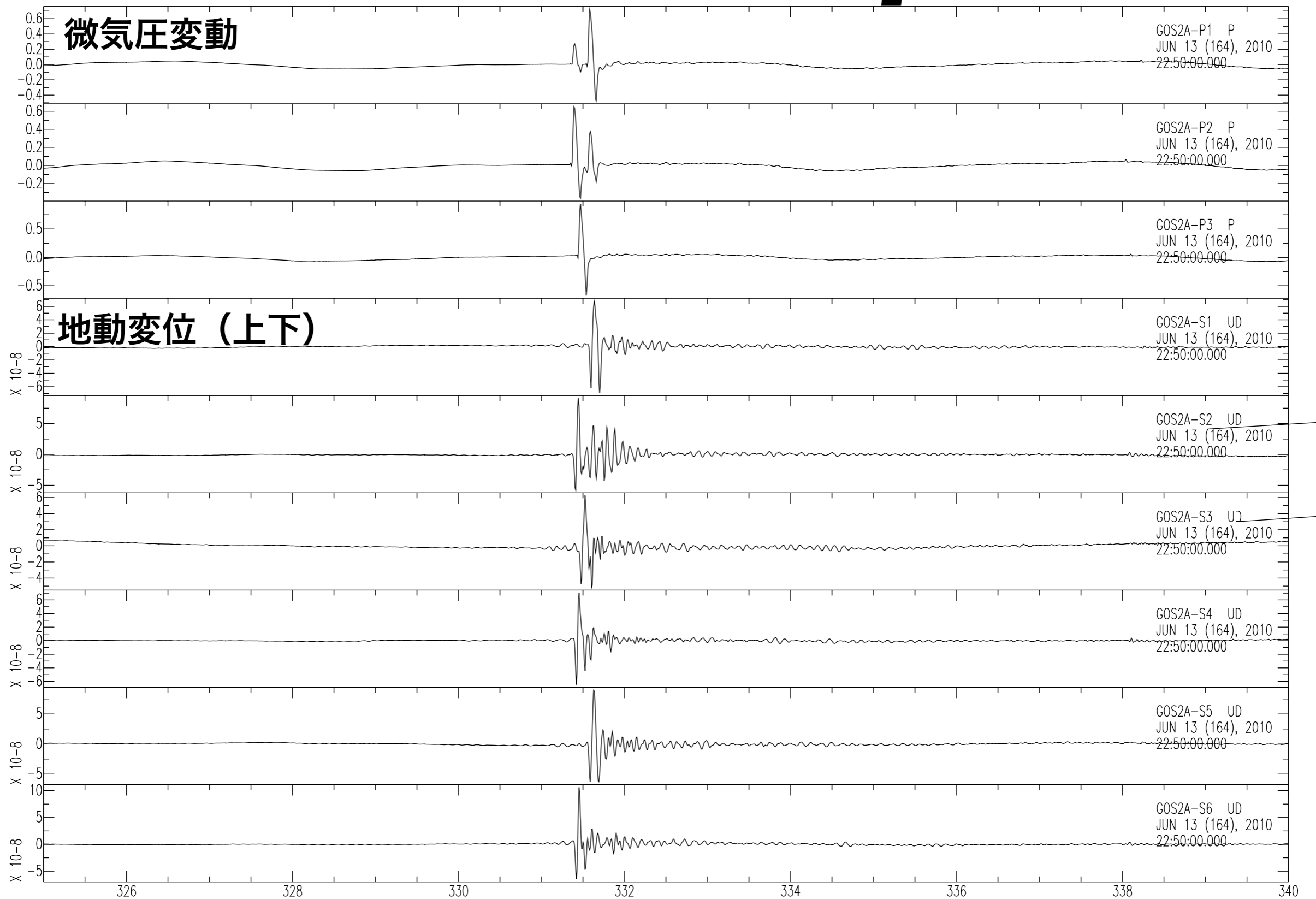
Audible Sound



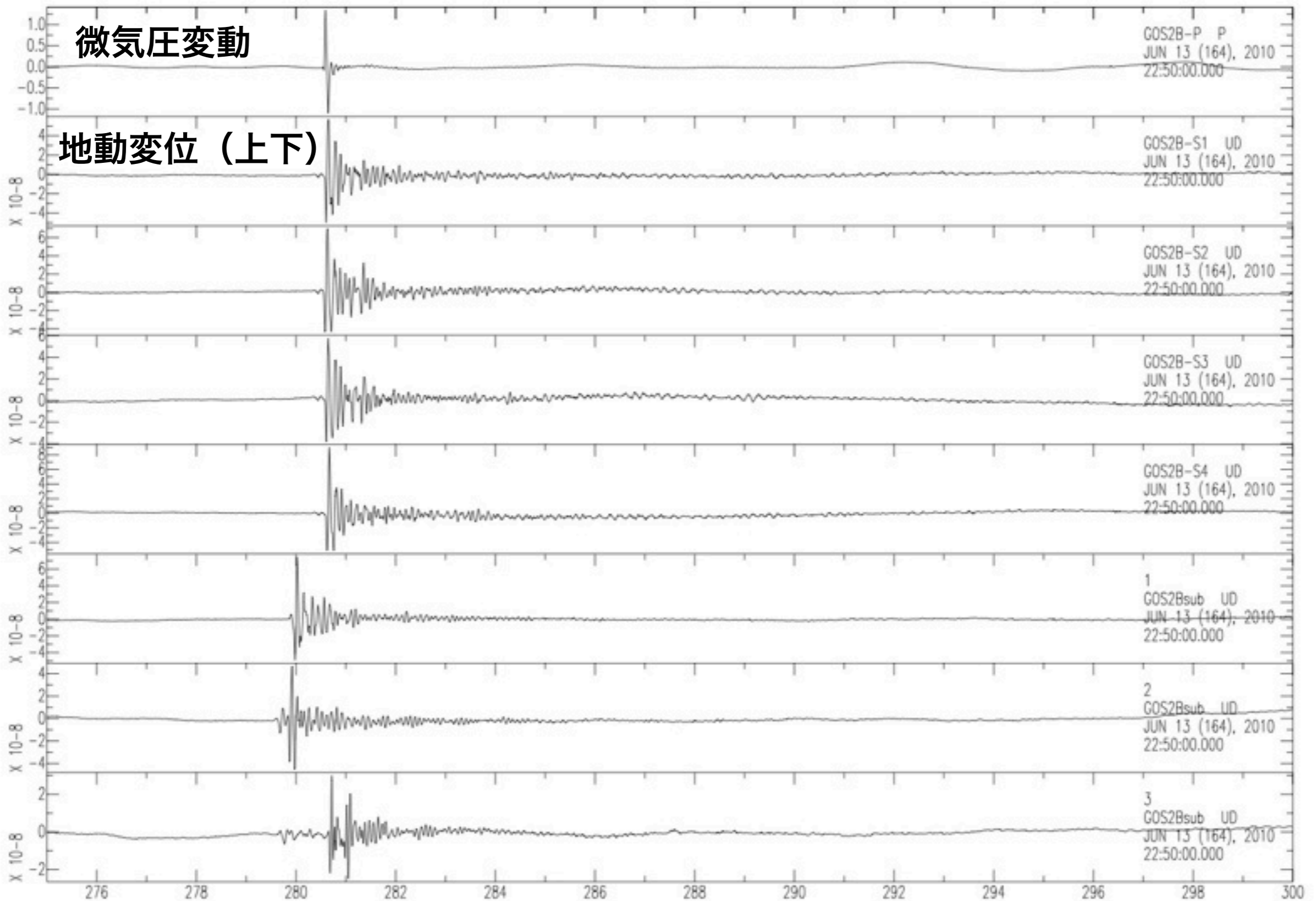
GOS2 waveform



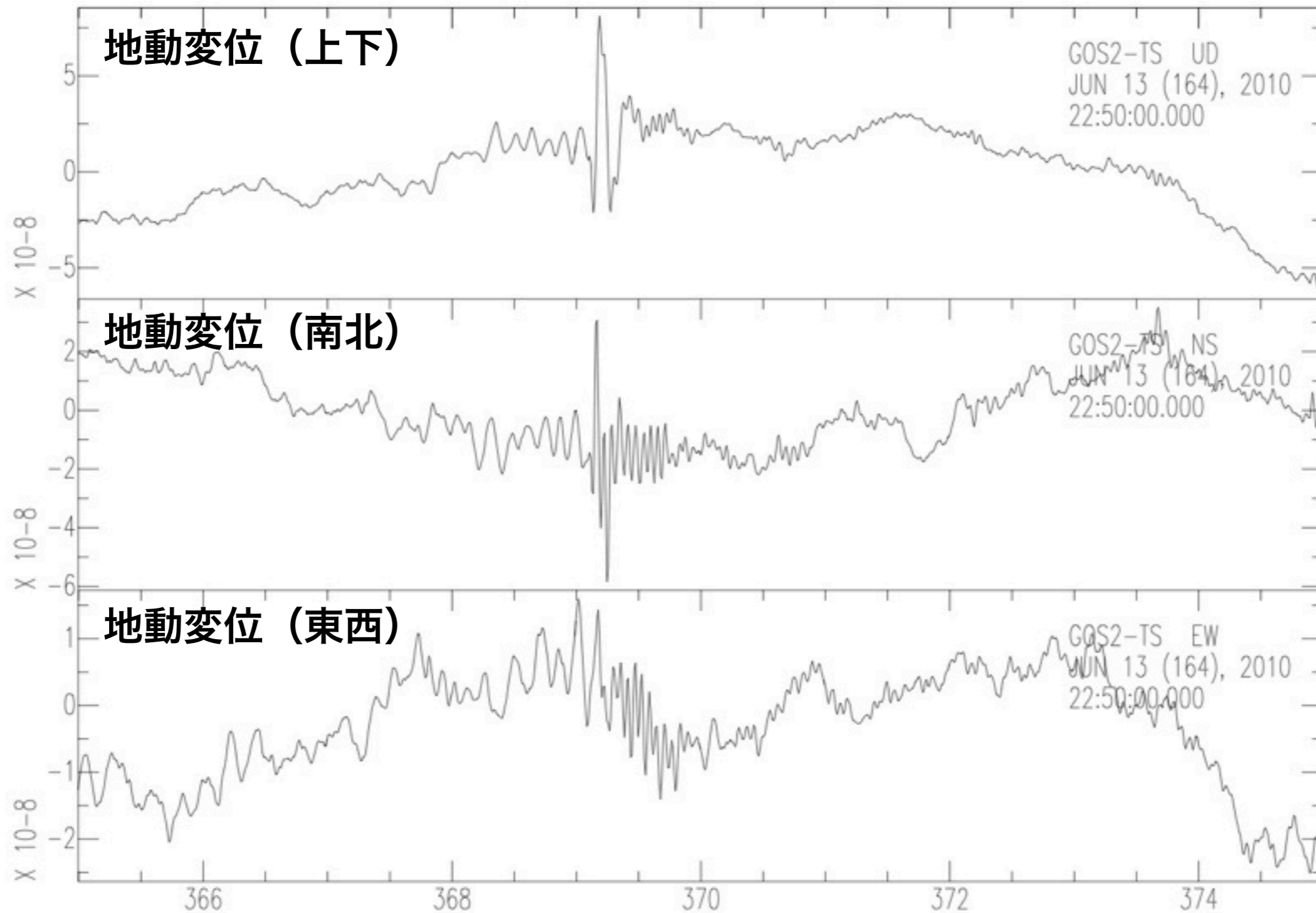
GOS2A waveform



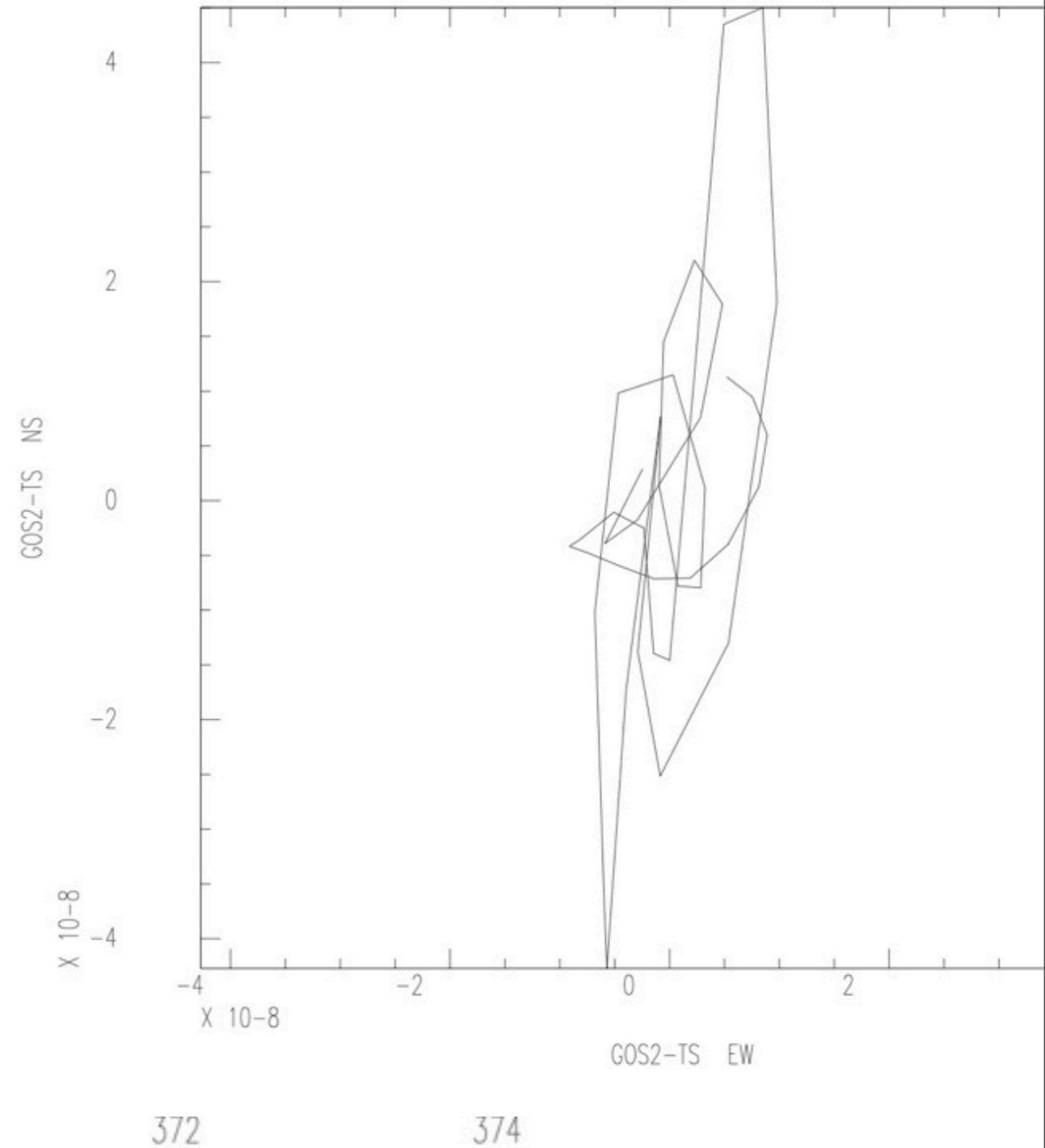
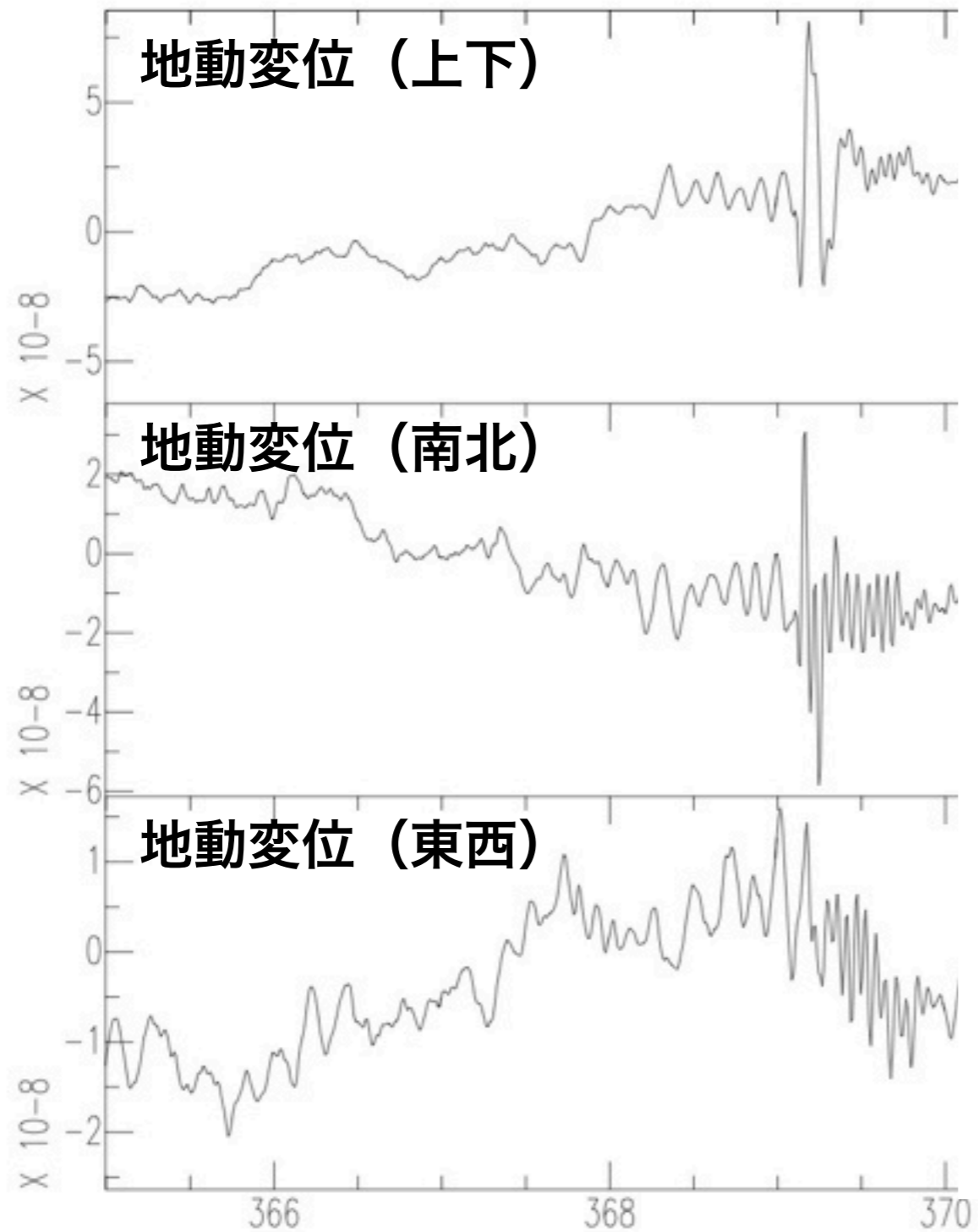
GOS2B waveform



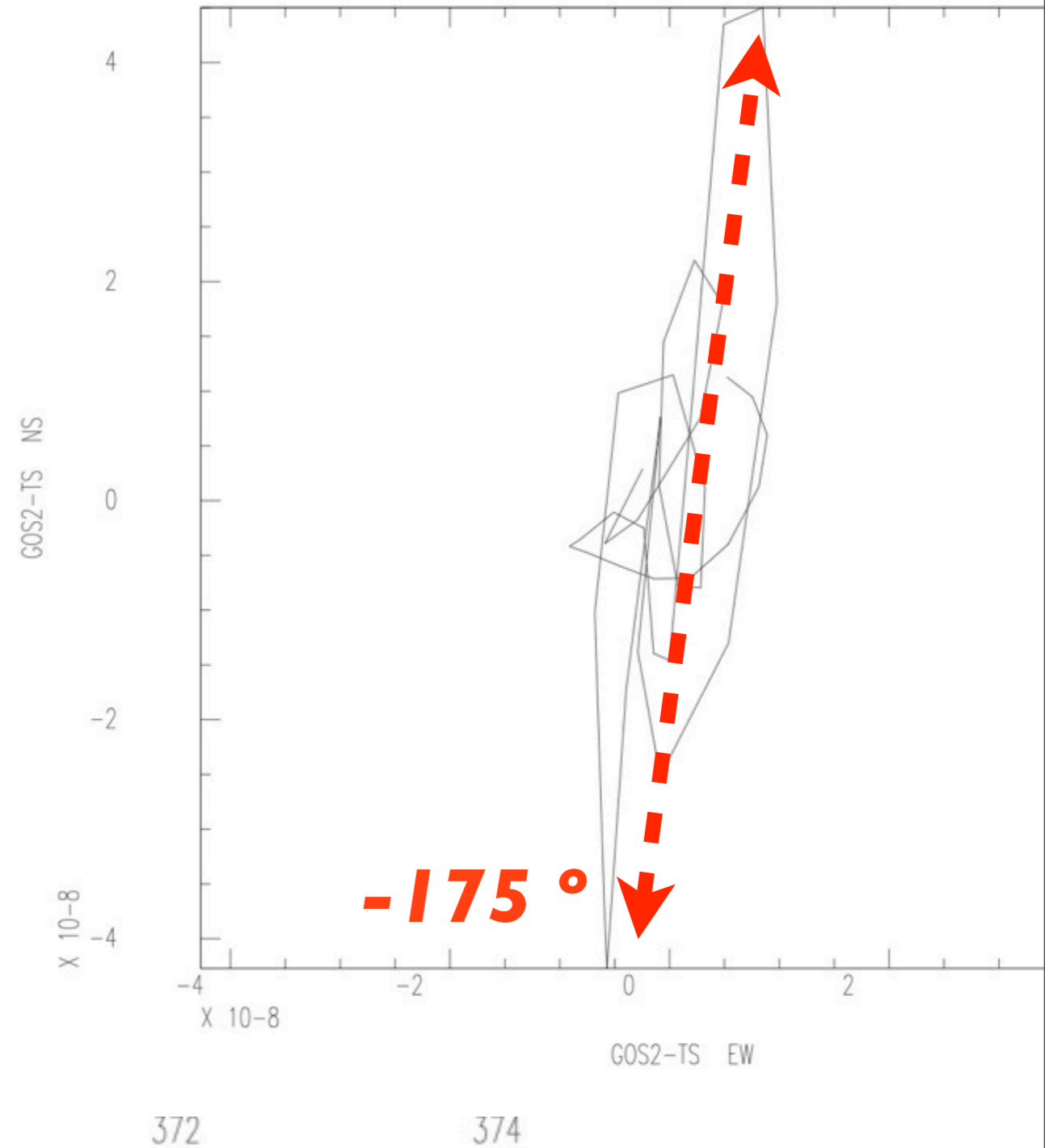
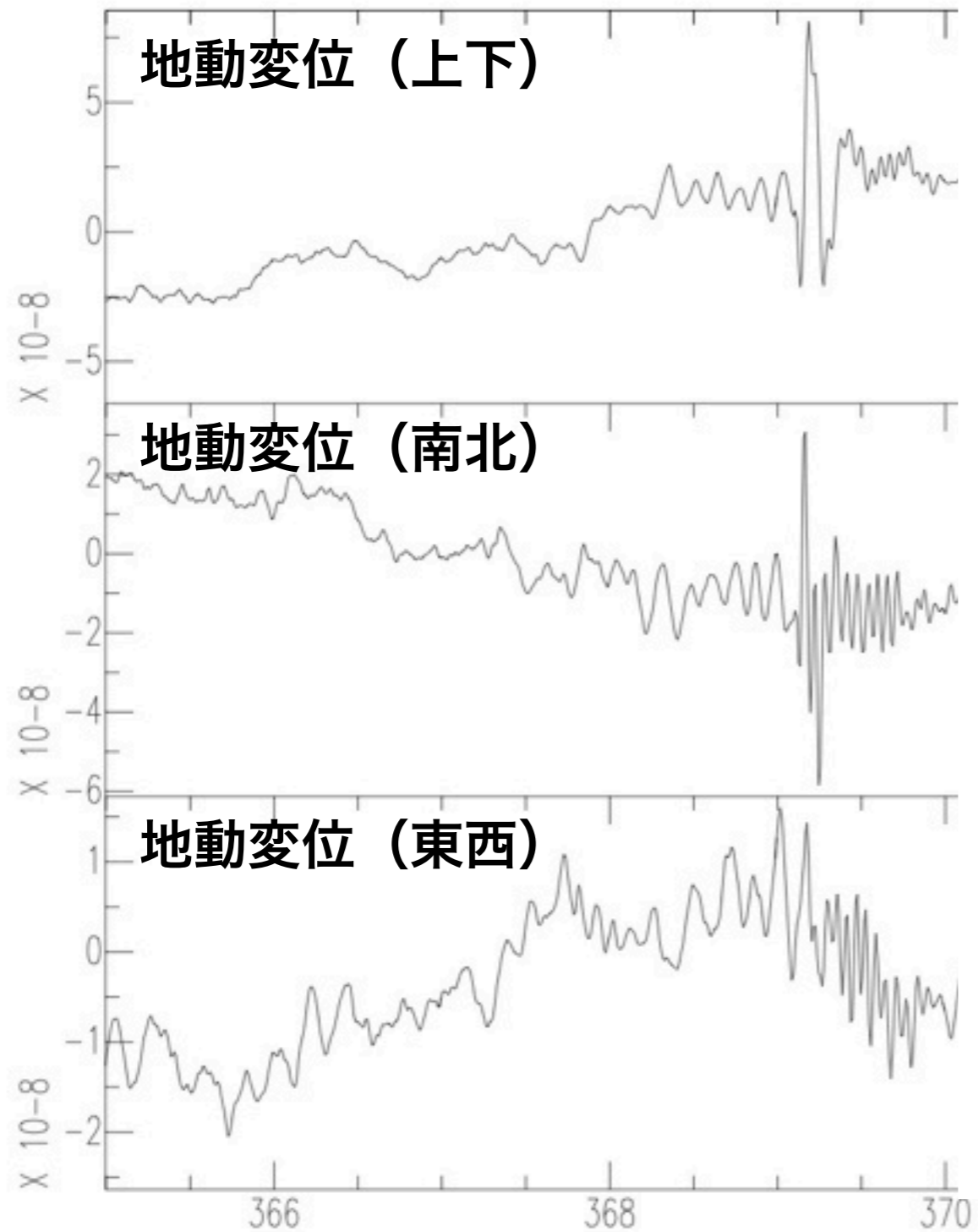
GOS2 *particle motion*



GOS2 *particle motion*



GOS2 *particle motion*

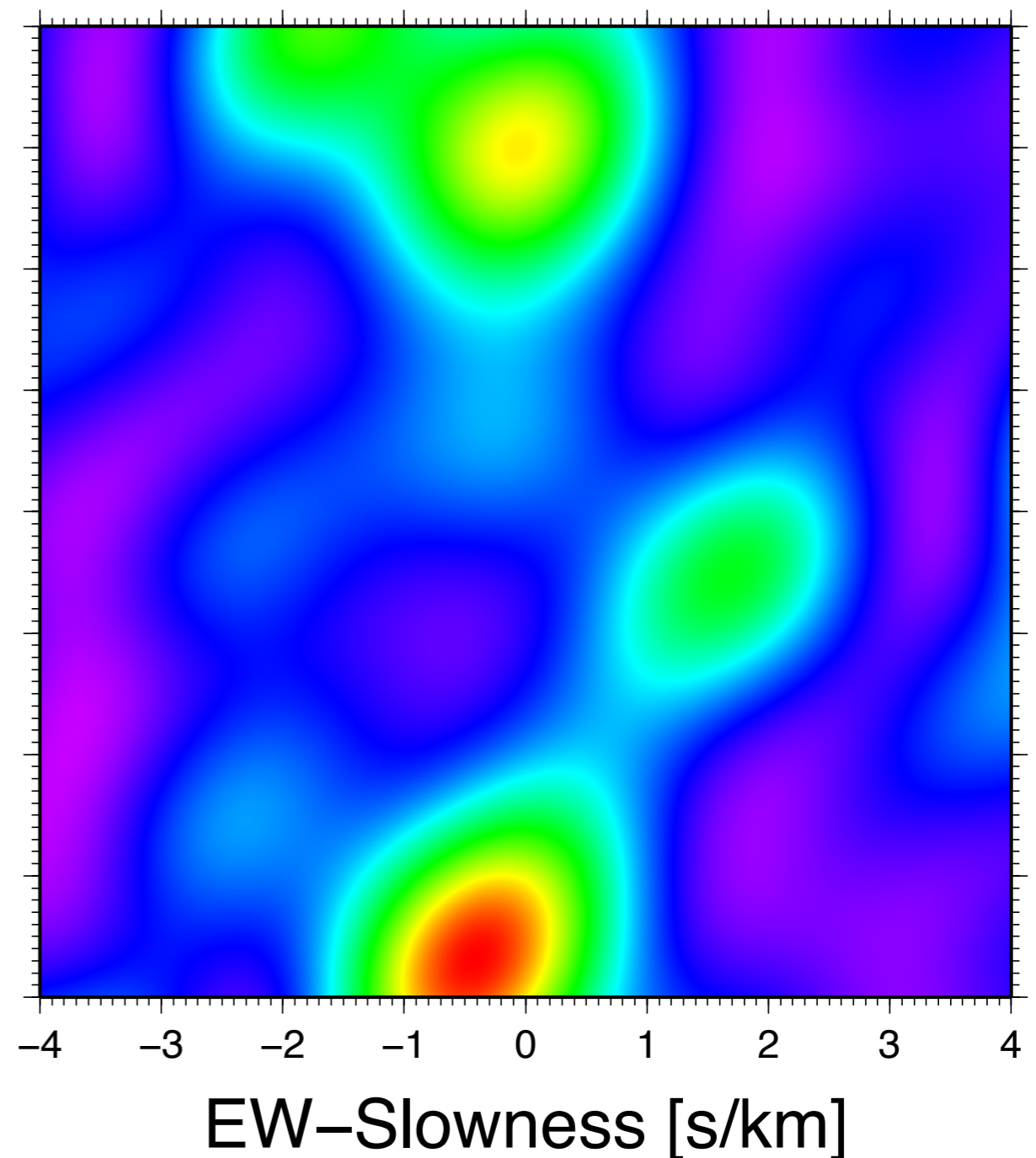
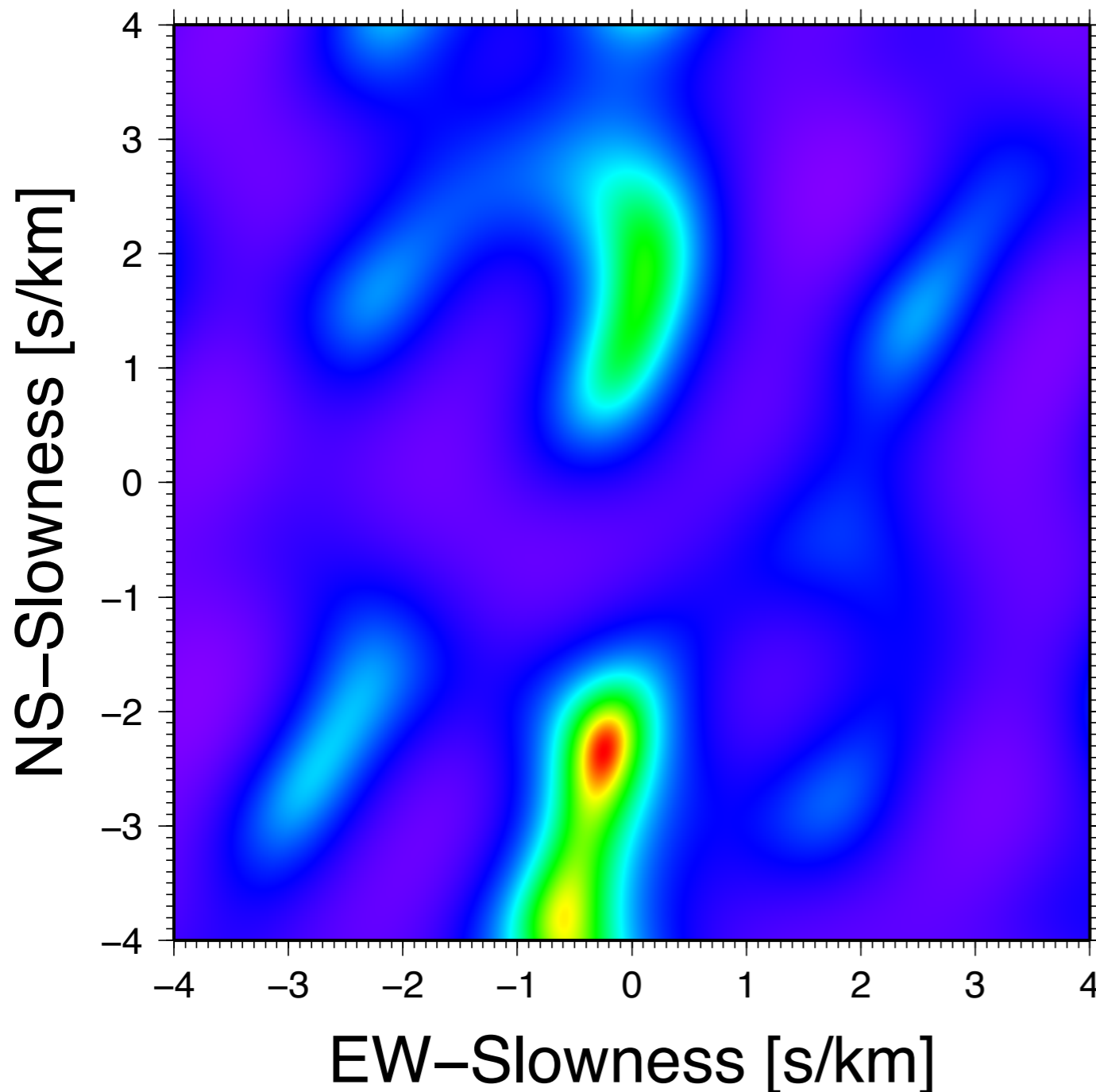


Array Analysis

(GOS2 1-10Hz Band)

MUSIC

Beam

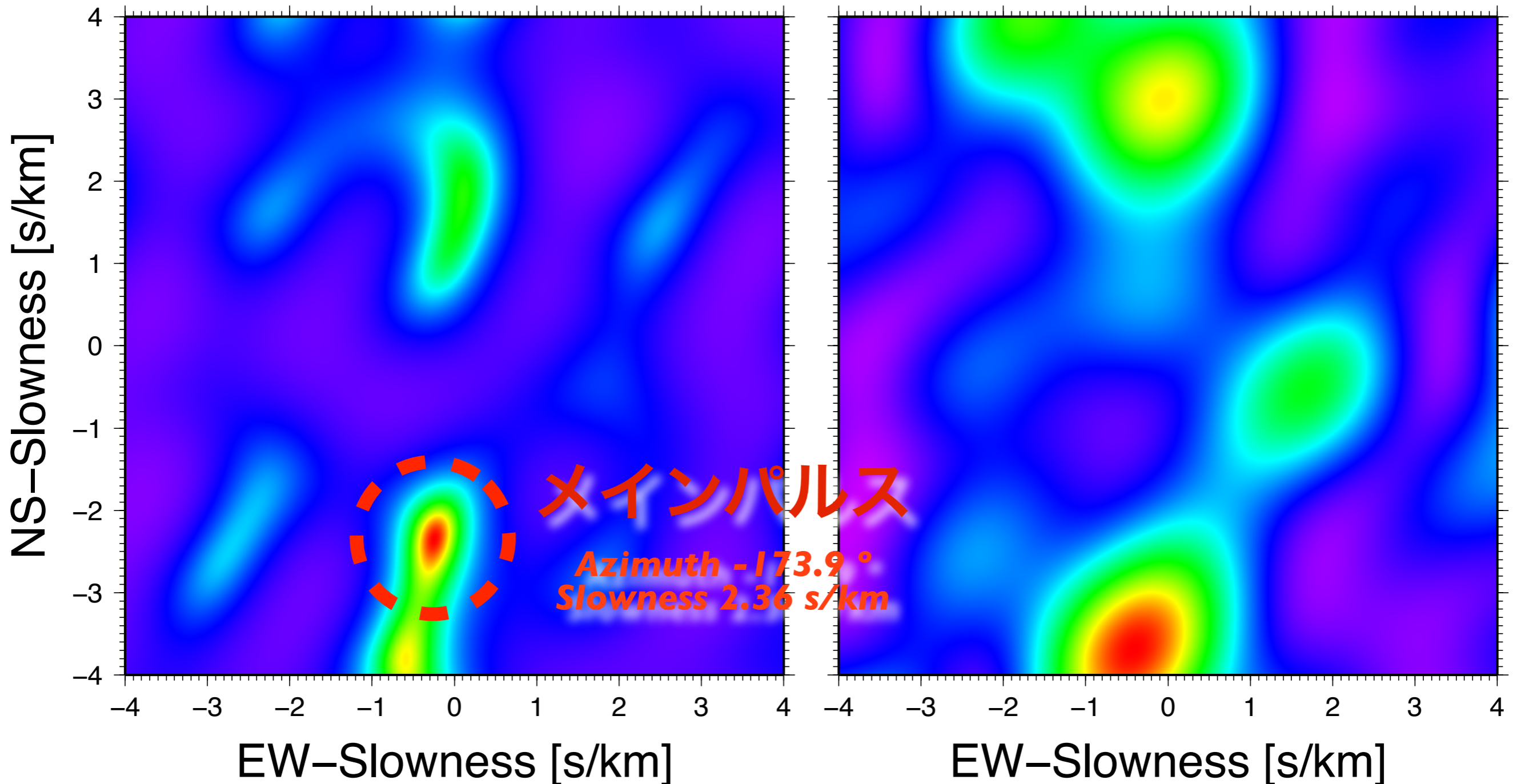


Array Analysis

(GOS2 1-10Hz Band)

MUSIC

Beam



SUMMARY

- HAYABUSA have Returned to the Earth at 13th June, 2010.
- HAYABUSA Reentry is Good Analogue of Meteorite Fall.
- We have Done Some Kinds of Observations as Follows...
 - * Optical Tracking
 - Determination of Trajectory
 - * TPS Science
 - Measurement of the Heating History of TPS
 - * Spectroscopy
 - Determination of What Elements Emit Light in the Meteor Head and Wake.
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