Teleseismic depth determination, techniques and uncertainties: an Himalayan case study

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Nepal
**Introduction**

**At regional distance**
- All range of magnitudes
- Relies on S-P delay
- Requires regional/local networks

**At teleseismic distance**
- Moderate-magnitude events (M>3.5)
- Relies on pP-P or sP-P delays
- Using Global Seismological networks (FDSN / IMS-CTBTO)

**Why improving depth determination?**
- Seismotectonic studies (Slab geometry, lateral variation of main tectonic structures)
- Discrimination between earthquakes and explosions
1- Techniques : Description of a teleseismic signal

Teleseismic wave = Direct wave (P) + P and S direct waves reflected on the Earth's surface (pP/sP)

Main characteristics of « depth phases » pP/sP:
• Recorded at stations between 30° (3000 km) to 90° (10000 km) away from the source
• Emitted rays are nearly verticals (< 30°)

Delays pP-P and sP-P are function of the hypocentral depth and the crustal velocity model above the source

Objective : Improving the detection of reflected waves « echoes » in the teleseismic signal
1- Techniques : Cepstrum analysis

- **Cepstrum**: « the power spectrum of the logarithm of the power spectrum »
- **Application**: Detection of echoes in a seismic signal  
  
  **Bogert et al., 1963**

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**Letort et al., 2014**: Automatic depth determination after station selection
1. **Techniques: Stack of Hilbert envelopes**

- **Cross-correlation + stack** of small-aperture arrays
- **Align** all waveforms on the direct phase using an improved kurtosis (Baillard et al., 2014) (filter: 0.8-2.5 Hz)
- **Lecture** of \( P-pP \) and \( P-sP \) table as a function of array distance and source depth - ak135 velocity model
- **Depth migration** of stacked signals: \( P-PpP / P-sP \) (time \( \rightarrow \) depth)
- **Sum of Hilbert envelopes** at each station for each case (\( P/pP / sP \))

A **manual** method for picking depth phases (interactive figure)

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**Hilbert transform**
Linear operator given by the signal convolution with the function \( \frac{1}{\pi t} \)

**Other depth determination techniques:**
- Waveform inversions (i.e. Abe, 1974; Langston, 1976)
- Global array stacking and source deconvolution (Craig et al., 2018)
- Stacking distance-variable window on binary functions representing potential arrival (Murphy and Barker, 2006)

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**Disclaimer:** The views expressed on this presentation are those of the author and do not necessarily reflect the view of the CTBTO.
2- Data: Selecting world-wide datasets

1 - Chili
- Hypocentral depths: [0-300] km
- Regional constraints:
  10,000 events + uncertainties (Sippl et al., 2018)
- Teleseismic depths catalogs (4 sets):
  ISC-EHB depths
  Source deconvolution (Craig et al., 2018)
  + Sum of Hilbert envelopes
  + Cepstrum analysis (based on Letort et al., 2014)

✓ 1st objective:
Validation of teleseismic depth determination techniques
Comparison between global networks FDSN/IMS
1 – Chili: Large dataset of moderate magnitude events (M>4) with a wide-range of depths

2 - Nepal
- Hypocentral depths: [0-25] km
- Regional constraints:
  38 events (ML> 3.5) + uncertainties (Laporte et al., 2021)
- A distance télesismique:
  ISC -EHB depths
  + Sum of Hilbert envelopes
  + Cepstrum analysis

✓ 2nd objective:
Finding limits of teleseismic depth determination techniques for shallow events
2a – Far Western Nepal: Dataset of moderate magnitudes (ML>3.5) shallow events
2b – Central Nepal: Multi-technique study of the 2021 Lamjung seismic crisis
Case study n°1: Northern Chile Forearc

Comparison of teleseismic depths (Cepstrum, Hilbert) with regional depths

IMS
Mean Nobs*: 10 arrays
Mean processing time: 15 sec

FDSN
Mean Nobs*: 800 stations
Mean processing time: 1000 sec

65% of Cepstrum depths within +/- 10 km of local depths
70% of Hilbert envelopes within +/- 10 km of local depths
71% of Cepstrum depths within +/- 10 km of local depths
78% of Hilbert envelopes within +/- 10 km of local depths

*Nobs: Number of observations

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Case study no.1: Northern Chile Forearc

- Seismic data from only two IMS stations (TX01/RCBR)
- Sum of Hilbert envelopes of events projected on track A-B
  - Cross correlation on mini-arrays (cc > 0.75)
  - Filtering 0.8 – 2.5 Hz
  - SNR > 3

Objectives:
- To recover the chilean slab geometry using Hilbert envelopes of ~1000 events
- To provide an image of the lateral variations of the slab

Using Hilbert envelopes for seismotectonic studies
(Letort et al., 2018 – Guerrero, Mexico)
Case study n°1: Northern Chile Forearc

The energetical content of Hilbert envelopes reproduces the lateral variations of seismicity at depth

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Why an Himalayan case study?

- High seismicity rates
- Nepalese seismicity occurs mainly between 10-25 km depth
- Studying the relation between shallow earthquakes and the Main Himalayan Thrust Fault (MHT)
Case study n°2.a: Far-Western Nepal

Comparison with depths from the HiKNet temporary seismological experiment (2014-2016)

38 events recorded at both regional and teleseismic distances with strong regional constraints

- 17 events considered as High Quality locations
  \((nP>6, nS>3, \text{rms}<0.4, \text{ERZ}<2, \text{ERH}<2)\)

Example - MLv 5.2 - 2015.12.18 earthquake
Event located at the base of the mid-crustal ramp

Comparison between Teleseismic (Hilbert) And Regional (Hypo71) depths

5 events /17 within 2 km of regional depth
12 events /17 within 5 km of regional depth
3 events /17 without adequate teleseismic depth
Case study n°2.b:
Regional and Teleseismic joint analysis of the Lamjung seismic crisis (Central Nepal)

Koirala B., Bollinger L., Guilhem-Trilla A., Laporte M., Daria, Wendling-Vasquez N., Letort J.,

Lamjung seismic crisis:
- **Mainshock**: MLv 5.5/Mw 4.69 – 2021.05.18-23:57:57 (UTC)
- Followed by 110 aftershocks within 5 days
- No signs of seismic swarm-like migration
Case study n°2.b :
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Four depths solutions for the mainshock :
• **10,75 km**: Hypo71 (absolute, regional)
• **13,8 km**: HypoDD (relative, regional)
• **17 km**: Cepstrum analysis – MT inversion
• **25 km**: MT inversion

→ **Uncertainties** : Regional velocity model (+/- 5km) (Adhikari, 2021), network geometry (regional only), topography (-3km), complex slab geometry, teleseismic wave interferences?
Conclusion

Objectives:

- Development of a new manual method for determining hypocentral depth from global teleseismic network using the Hilbert envelopes of teleseismic waveforms
- Using regional seismic catalogs with well-constrained depths to point out errors in the depth determinations at teleseismic distance
- Highlighting lateral variations of geometry of large tectonic structures (slab, megathrusts...) using projections of Hilbert envelopes of large seismic datasets seen at one or two teleseismic stations

Results:

- Comparisons of teleseismic depths with depths constrained by regional seismological networks (Chile, Nepal)
  → In Chile: 71% of teleseismic depths within +/-10 km of regional depths (out of 100 events)
- Projections of stacked Hilbert envelopes of 1000 earthquakes recorded at TX01 and RCBR highlights lateral variations of the northern chilean slab
- Determination of the limits of each depth determination technique: for shallow events in complex tectonic environments conjoint studies of regional and teleseismic depth determination techniques do not always succeed to find a common depth result

Perspectives:

- Quantification of uncertainties and their propagation into the Cepstrum analysis and Hilbert technique
- Finding source of depth errors for the Lamjung crisis
- Application of the projection of Hilbert Envelopes for Himalayan regions
References for the Cepstrum analysis:


References for Chile:


References for Nepal:


Other teleseismic depth techniques: