Comment on "An Evaluation of the Timing Accuracy of Global and Regional Seismic Stations and Networks" by Yang et al. (2021)

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Xin Zhang[1] (zx2019@mail.ustc.edu.cn), Lianxing Wen[2]
1. University of Science and Technology of China, Hefei, Anhui 230026, China; 2. State University of New York at Stony Brook, Stony Brook, NY 11794, USA

Claims in Yang et al. (2021) and DI31C-02 (Yang & Song)

- **Prevailing large clock errors in global seismic stations**

  Recently, Yang et al. (2021) (YSR21) estimated clock error in a seismic station based on the residual of the relative time shift ($\mathrm{d}t_{\mathrm{res}}$) of *P* waves among repeating earthquakes (doublets) and reported over 5000 probable "clock errors" ranging from tens of milliseconds to over 10 s at global and regional stations from IRIS DMC.

  Such a claim of widespread clock errors of seismic instruments, if it were true, would be a great warning to the network operators and raise doubts on the integrity of many studies that relied on accurate timing to tens of milliseconds, such as the studies of temporal changes in Earth's structure.

  Definition of a possible "clock error" in a seismic station:

  $$\text{"clock error"} = \mathrm{d}t_{\mathrm{res}} = \mathrm{d}t_{\mathrm{obs}} - \mathrm{d}t_{\mathrm{pre}}$$

  (Yang et al., 2021)

  - $\mathrm{d}t_{\mathrm{obs}}$: *the time shift of the phase pair in the observation measured by cross-correlation*
  - $\mathrm{d}t_{\mathrm{pre}}$: *the time shift of the phase pair due to source location differences and correction of origin time from relocation*

- **Misidentification of reported inner core boundary temporal changes**

  In particular, they made an example of reported temporal changes of the inner core boundary (ICB) based on a doublet SSI_1993-2003 by Wen (2006) for three stations:

Station	"Issues" in ICB observation
AAK	"Clock error" of 65 ms estimated from doublet D1_1995-2003
OBN	"Clock error" of 93 ms estimated from doublet D2_1993-2004
ARU	Instrument response changes

  YSR21 claimed "We further demonstrate that the original observations of the temporal change by Wen (2006) can be explained entirely by correcting for the instrument response and timing errors" and that the reported temporal changes of the ICB in Wen (2006) were a "misidentification". The claim was repeatedly cited in their publications and is also repeated in a poster in this meeting: DI31C-02 (eLightning; by Yi Yang and Xiaodong Song).

In this poster,

- we examine their claims with a focus on the reported "problematic" stations AAK and OBN and the two associated doublets they emphasized in the inner core study;
- we show that the effect of instrument changes can be simply corrected by deconvolution and present the temporal change of PKiKP at ARU after the correction.

Concluding remarks

- Forward calculations show 3 issues in YSR21: large errors in relocation results, questionable selection of "problematic stations" and unreproducible "clock errors" of AAK and OBN.
- Our relocation and reanalysis of the doublet dataset indicate no clock error at OBN and no justifiable claim of a clock error at AAK. YSR21's manual shifts by "clock errors" at the OBN and AAK observations in Wen (2006) are not justified.
- Along with a correction for the updated instrument response changes at station ARU that exhibits PKiKP travel time temporal change of 50 ms at that station, our study confirms the reported temporal change of the ICB in Wen (2006).
- **NOTE**: YSR21 has recently published a correction after receiving our comment. We examined their correction and found the correction does not alter the major conclusions here.

(Erratum to YSR21)

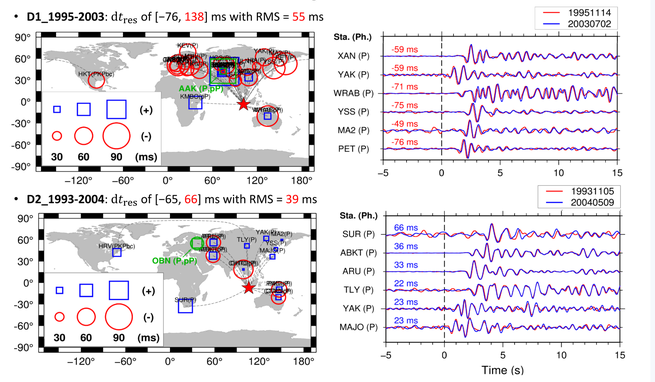
1. Evaluation of YSR21's results: 3 issues

- **Large errors in YSR21's relocation of doublet**

  Relocation of the doublet determines the computed $\mathrm{d}t_{\mathrm{pre}}$ of a phase pair and thus the estimation of clock error of a station. A straightforward way to evaluate the accuracy of a doublet relocation result is to forward calculate $\mathrm{d}t_{\mathrm{res}}$ based on the result. A good relocation result should generate little residuals and excellent waveform alignments between the doublet in the individual stations.

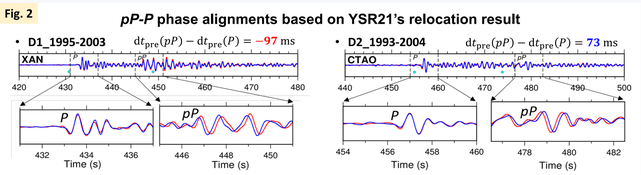
  a) Large errors as shown in predicted $\mathrm{d}t_{\mathrm{res}}$ and waveform alignments at individual stations (Fig. 1)

Fig. 1 **Predicted residuals and waveform alignments from YSR21's relocation result**



  b) Large errors as shown in prediction of relative travel times of *pP-P* phases (Fig. 2)

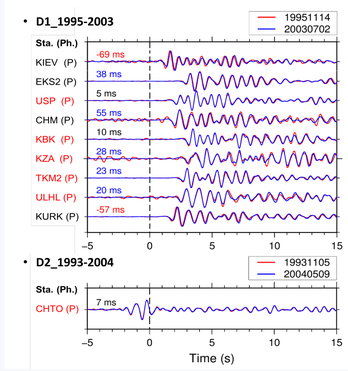
Fig. 2 ***pP-P* phase alignments based on YSR21's relocation result**



- **Questionable selection of "problematic stations" of "clock errors"**

  The reported "problematic" stations with "clock errors" in YSR21 are not supported by their relocation results, with some (with station name marked in red) reported "problematic" ones exhibit smaller P-wave $\mathrm{d}t_{\mathrm{res}}$ than the claimed error bound of ±30 ms (Fig. 3).

Fig. 3 **Listed "problematic stations" in YSR21**



- **Unreproducible "clock errors" at AAK and OBN**

  With the $\mathrm{d}t_{\mathrm{obs}}$ and the relocation results reported in YSR21, the YSR21's claimed "clock errors" at stations AAK and OBN are not reproducible.

Station	AAK	OBN
Recalculation of YSR21	$\mathrm{d}t_{\mathrm{res}} = \mathrm{d}t_{\mathrm{obs}} - \mathrm{d}t_{\mathrm{pre}}$, with • $\mathrm{d}t_{\mathrm{obs}}$: same values as reported in YSR21; • $\mathrm{d}t_{\mathrm{pre}}$: computed from YSR21's relocation results with the same reference model; confirmed by TauP and ttimes.	
	23 ms	132 ms
YSR21's report	65 ms	93 ms

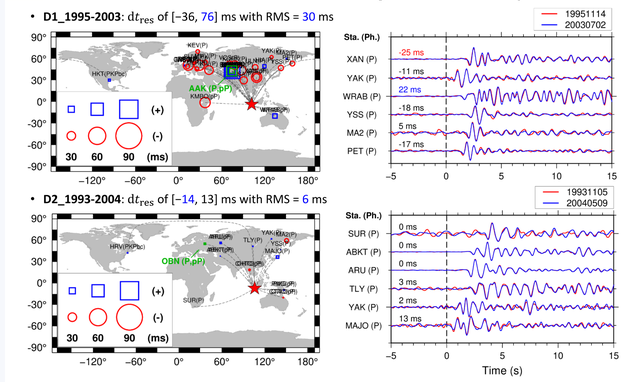
2. Reanalysis: Doublet Data & "Clock Errors" at AAK and OBN

- **Relocation of the two doublets**

  We relocate the two doublets based on the master event approach (Wen, 2006), using global seismic data with high-quality non-IC phases *P*, *pP* and *PKPbc* from IRIS. Our relocation results are verified to have smaller $\mathrm{d}t_{\mathrm{res}}$ and better waveform alignments at individual stations (Fig. 4) and smaller *pP-P* residuals (Fig. 5).

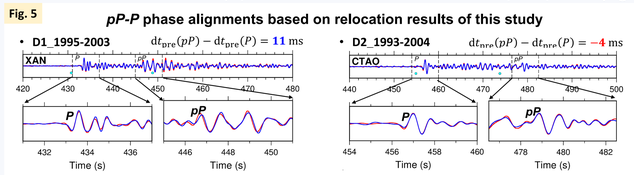
  a) Evaluation of relocation accuracy: predicted $\mathrm{d}t_{\mathrm{res}}$ and waveform alignments (Fig. 4)

Fig. 4 **Predicted residuals and waveform alignments of this study**



  b) Evaluation of relocation accuracy: prediction of relative travel times of *pP-P* phases (Fig. 5)

Fig. 5 ***pP-P* phase alignments based on relocation results of this study**

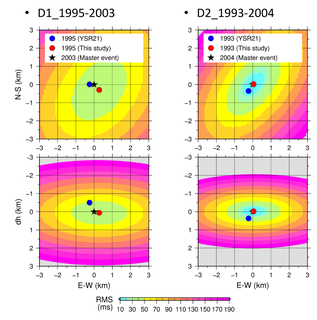


  c) Comparison of two relocation results (Fig. 6)

  Our relocation results differ from those of YSR21 for both doublets, in both the relative horizontal locations and relative depths.

	D1_1995-2003				D2_1993-2004			
	az	dX (m)	dh (m)	dO (s)	az	dX (m)	dh (m)	dO (s)
YSR21	272°	251	−499	1.9186	137°	407	58	2.1537
This study	213°	424	370	1.9227	63°	49	−22	2.1538

Fig. 6 **Relocation results**



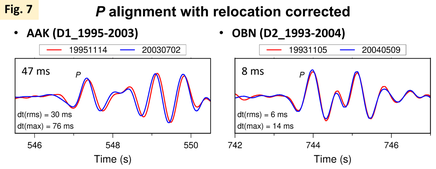
- **Reanalysis of clock errors at AAK and OBN**

  Based on our relocation results, $\mathrm{d}t_{\mathrm{res}}$ at AAK and OBN are 47 ms and 8 ms respectively (Fig. 7).

  a) AAK: no justifiable clock errors. The doublet used has a relatively large relocation error so that the doublet is not a good candidate event pair to use to detect clock errors, and it is not appropriate to attribute the 47-ms residual to a "clock error";

  b) OBN: no clock errors.

Fig. 7 ***P* alignment with relocation corrected**



3. Unfounded Claim of "Misidentification of the Temporal Change of the ICB in Wen (2006)"

(Wen, 2006)

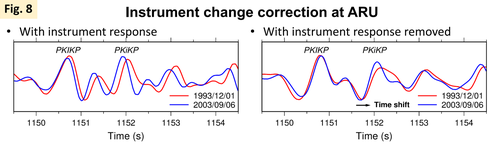
- **"Timing error" related ICB observations: AAK & OBN**

  As shown in our relocation results and reanalysis of residuals at the two stations, no clock error at OBN and no justifiable clock error at AAK are needed to be "corrected" (Fig. 7). The manual shifts by "clock errors" of YSR21 at the OBN and AAK observations of Wen (2006) are not justified.

- **Instrument change related ICB observations: ARU**

  By removing the respective instrument responses, the apparent time shift between the responses of different seismic instruments can be simply corrected. After the removal of the effect of different instrument responses at ARU, a 50-ms time offset of PKiKP phases is evident in the waveform alignments of the corrected data (Fig. 8).

Fig. 8 **Instrument change correction at ARU**



Reference

- Zhang X. and Wen L., Comment on "An Evaluation of the Timing Accuracy of Global and Regional Seismic Stations and Networks" by Yang et al. (2021) *Seismol. Res. Lett., accepted pending the completion of the reply from the commented authors*.
- Yang Y., X. Song and A. T. Ringler, 2021. An Evaluation of the Timing Accuracy of Global and Regional Seismic Stations and Networks, *Seismol. Res. Lett*.
- Wen L. (2006). Localized Temporal Change of the Earth's Inner Core Boundary, *Science*.
- See also: DI31C-02 (eLightning) by Yang Y. and Song X.