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On waveform correlation measurement uncertainty with implications for temporal changes in inner core seismic waves

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ABSTRACT

We address the uncertainty related to cross-correlation waveform time shift measurements, particularly related to temporal changes in inner core seismic waves. Details of the cross-correlation measurement, including data processing, window length, pick time, sampling rate and the algorithm itself, all affect the calculated time shift. By systematically varying measurement parameters for a set of earthquake doublets we find time shift uncertainties of 0.01 s and 0.02 s for differential times and double differential times respectively. The uncertainty is of a similar magnitude to reported double differential times of PKIKP and PKiKP inner core phases. Accounting for measurement uncertainty results in 80% of values published in a recent study being below the measurement resolution (Yang and Song 2020a). While the temporal variations in inner core phases is not in dispute, properly accounting for uncertainties is needed for robust data interpretation. A re-assessment for the origin of inner core temporal changes is therefore warranted and future studies should account for measurement uncertainty.

1. Introduction

Many aspects of seismology rely on high resolution time shift measurements which are calculated by waveform cross-correlation. Notable examples are earthquake detection and re-location (e.g. Gibbons and Ringdal 2006; Waldhauser 2000), temporal monitoring of hydrocarbon reservoirs and sequestered carbon dioxide (e.g. Lumley 2010; Rickett and Lumley 2001), seismic tomography (e.g. Lawrence et al. 2006; Ritsema and van Heijst 2002), and analysis of inner core differential travel times (e.g. Shearer and Toy 1991; Song and Richards 1996). In order to achieve high resolution measurements, data is normally interpolated to a sampling rate higher than that it was acquired with. Most global broadband stations have a sampling rate of 20 Hz (a sample is recorded every 0.05 s), yet cross-correlation lag times are reported to have an accuracy of 0.001 s (e.g., Yang and Song (2020a, 2020b)). The uncertainty associated with these measurements is often ignored, yet it can have profound implications for the interpretation of data particularly when the time shifts in question are small.

Our study focuses on the cross-correlation measurement uncertainty of differential travel times of inner core phases. We focus on this area because many differential travel times reported are of a similar magnitude to the data sampling rate. Therefore we expect the measurement uncertainty to also be of a similar order to the differential times themselves. Furthermore, properly accounting for measurement uncertainty has implications for the origin of temporal changes in inner core seismic waves.

The travel time of seismic waves traversing the inner core (PKIKP) has been observed to change on decadal or shorter time scales (Creager 1997; Mäkinen and Deuss 2011; Song and Richards 1996; Tkalčić et al. 2013; Vidale 2019; Yang and Song 2020a; Yao et al. 2015; Yu 2015; Zhang et al. 2005). This temporal change in travel time was initially interpreted as due to differential rotation of the inner core with respect to the Earth's mantle (Song and Richards 1996; Creager 1997). However subsequent global observations of inner core rotation rates were incompatible, indicating that the origin of temporal changes in inner core travel time is likely not from rigid-body inner core rotation (Mäkinen and Deuss 2011). Additionally, temporal changes in the travel time of seismic waves reflecting from the inner core boundary (ICB, PKiKP phase, Fig. 1) indicate that ICB topography is changing over time (Wen 2006), which can also explain the observed PKIKP travel time change (Yao et al. 2015). Thus temporal changes in inner core phases (both PKIKP and PKiKP) travel times could instead originate from changing ICB topography over time.

The explanation for temporal changes in travel times of inner core

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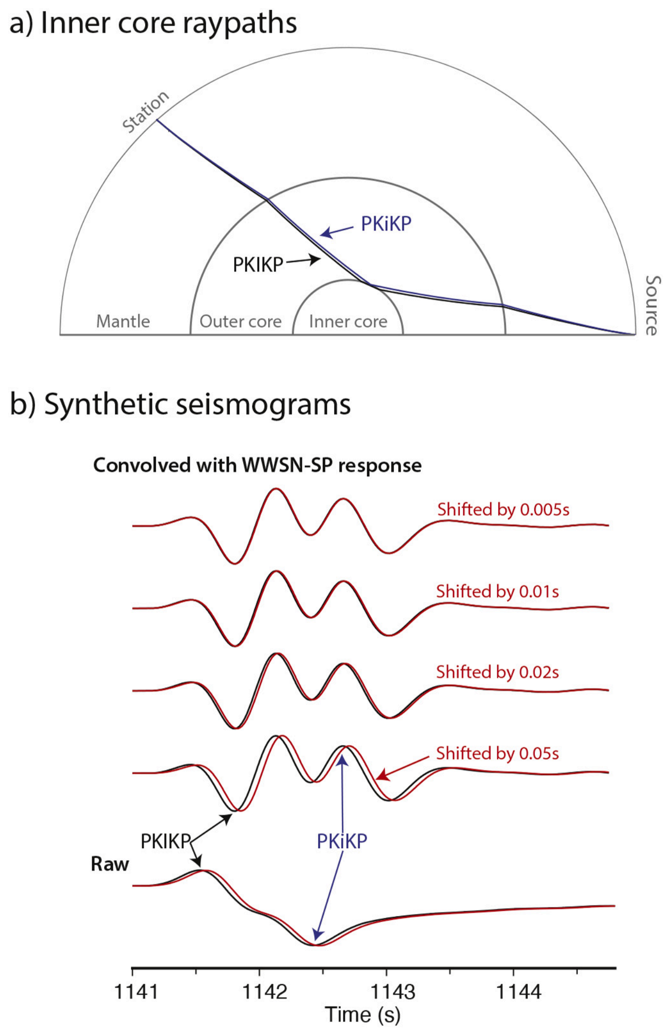


Fig. 1. a) Raypaths of PKIKP (black) and PKiKP (blue) waves. PKIKP travels through the inner core, while PKiKP reflects from the inner core boundary. b) Synthetic seismograms of PKIKP and PKiKP through a 1D Earth model PREM. Bottom waveforms are raw displacement waveforms. Top waveforms are filtered with the worldwide standard seismic network short-period (WWSN-SP) instrument response to leave a dominant period of ~1 s. Red waveforms are shifted later by 0.05 s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phase (i.e., solid-body rotation of the inner core or changes in ICB topography) is principally constrained by whether the travel time of PKiKP changes at a similar magnitude to the PKIKP phase. Yao et al. (2019), Yao et al. (2015) and Wen (2006) claim that both PKiKP and PKIKP experience temporal travel time changes and they can be explained consistently by ICB topography changes, while inner core differential rotation would provide an inconsistent explanation to the seismic data. On the other hand, Yang and Song (2020b) and Yang and Song (2020a) claim that temporal changes originate most (if not all) from the PKIKP phase or the inner core's interior rather than the PKiKP phase or the ICB, which is best explained by solid-body inner core rotation. The differential times of concern are on the order of 0.01 s, therefore accounting for measurements uncertainty is important as it will affect the resulting interpretation.

Temporal changes in inner core seismic waves are generally measured using earthquake doublets (e.g. Mäkinen and Deuss 2011; Song and Poupinet 2007; Song and Richards 1996; Wen 2006; Yang and Song 2020b; Yao et al. 2015; Yu 2015; Zhang et al. 2005). Earthquake doublets are pairs of earthquakes occurring in almost the same location with highly similar waveforms. Doublets that are separated in time allow the accurate measurement of changes in the travel times of seismic phases over that time period. In order to attribute temporal travel time changes to variations in the medium properties, factors such as instrument errors, earthquake origin time and hypocentre location differences must first be accounted for. Although there is some debate over how well these factors can be minimised (Song 2000; Sun et al. 2006), attempts are generally now made to correct for them (Yao et al. (2015, 2019)). However, one source of uncertainty that is often ignored is the measurement uncertainty when sub-sample accuracy is required. Yao et al. (2015) and Yao et al. (2019) estimated a measurement uncertainty of 0.01 s associated with PKIKP and PKiKP travel time change based on personal experience, but did not perform any systematic error analysis. Here we quantify the measurement uncertainty first by analysing synthetic seismograms and then by using several earthquake waveform doublets commonly used in studies of the temporal change of inner core phases (Yang and Song (2020a), Yao et al. (2015, 2019), Wen (2006)). We find that only ~20% of the measurements presented in a recent work (i.e., Yang and Song (2020a)) have a value greater than the measurement uncertainty.

2. Data and Methods

Our focus is the change in travel time of PKIKP and PKiKP phases from earthquake doublets as commonly used in inner core differential time studies. Analysing these two phases can be challenging, partly because their temporal separation is difficult - for example PKIKP and PKiKP are predicted to arrive less than 1 s apart for epicentral distances less than 133° (PREM Earth model). Additional complications arise because PKiKP is not simply a polarity reversal of PKIKP – the phase shift between PKiKP and PKIKP varies from ~120° to 163° in the distance range of 130° to 144° (Cao and Romanowicz 2004). Waveforms are also affected by diffractions from the ICB, multi-pathing and waveform broadening due to attenuation.

In order to quantify uncertainties in cross-correlation measurements of inner core phases, we first analyse measurement uncertainties in synthetic seismograms before looking at real data. We initially use synthetic seismograms in order to verify the effectiveness of various cross-correlation algorithms for inner core waveforms that are not affected by complexities such as heterogenous Earth structure, complex source functions or ambient noise. We then turn our attention to real data and analyse several waveform pairs from earthquake doublets, in order to assess how different measurement parameters affect the resulting differential time shifts measured in real data contaminated with additional complexities.

The principle uncertainties in cross-correlation originate from i) the algorithm itself and data processing therein, ii) data interpolation, iii) time window length, and iv) the pick time. Similar to uncertainty analysis for seismic monitoring of hydrocarbon reservoirs (e.g. Ji et al. 2019), we determine the uncertainty associated with waveform cross-correlation of inner core phases by systematically varying the algorithm and measurement parameters used. We investigate four cross-correlation algorithms, implemented in both the time and frequency domain. The algorithms 'sac_wfcc' and 'cc_sac' calculate cross-correlation in the frequency domain. Both codes are open source, the first algorithm is commonly used in the seismology community (Peng 2013) and the second is used to search earthquake doublets to study temporal change of inner core phases (Yao et al. 2015). We also use two cross-correlation algorithms in MATLAB which are in the time and frequency domain (Buck et al. 2002). We find that both the MATLAB algorithms produce the same result and so only show the results from one. Differences in the frequency domain methods is principally from tapering applied in the time domain before the Fourier transform to minimise spectral leakage. The 'cc_sac' and 'sac_wfcc' algorithms apply hanning and cosine tapers, while the MATLAB frequency domain algorithm does not perform any tapering and pads the time series with 0's.

Table 1
Ten waveform pairs analysed in this study based on data compiled by Yao et al. (2015).

Waveform Number	Station Code	Date	Network Code	Event Latitude (°N)	Event Longitude (°E)	Depth (km)	Mag (m_b)
1	AAK	12/1/93	II	−57.475	−25.685	33.0	5.5
		9/6/03	KN	−57.478	−25.688	33.7	5.6
2	ARU	12/1/93	II	−57.475	−25.685	33.0	5.5
		9/6/03	II	−57.478	−25.688	33.7	5.6
3	XAN	12/1/93	IC	−57.475	−25.685	33.0	5.5
		9/6/03	IC	−57.478	−25.688	33.7	5.6
4	LVZ	12/1/93	II	−57.475	−25.685	33.0	5.5
		9/6/03	II	−57.478	−25.688	33.7	5.6
5	AAK	4/12/98	KN	−56.116	−26.768	100.0	4.7
		23/3/2004	KN	−56.115	−26.766	99.9	4.9
6	AAK	23/3/2004	KN	−56.115	−26.766	99.9	4.9
		12/2/09	KN	−56.116	−26.768	100.1	5.4
7	AAK	4/12/98	KN	−56.116	−26.768	100.0	4.7
		12/2/09	KN	−56.116	−26.768	100.1	5.4
8	ARU	30/7/1998	II	−58.808	−25.273	33.0	5.1
		9/6/13	II	−58.809	−25.272	33.1	5.3
9	ARU	4/12/98	II	−56.116	−26.768	100.0	4.7
		12/2/09	II	−56.116	−26.768	100.1	5.4
10	ARU	29/9/2003	II	−55.714	−26.921	33.0	4.9
		24/3/2010	II	−55.714	−26.921	33.0	4.9

The 'sac_wfcc' applies additional data interpolation before cross-correlation. We investigate different window lengths, from 0.7–1 s, centred on the travel time picks. A window length of ~1 s is used in the PKIKP/PKiKP studies of Yang and Song 2020a, while 0.8 s is used by Yao et al. (2015). Lastly, the data is interpolated to sampling rates of 0.01 s and 0.001 s (Yang and Song (2020a) use 0.001 s, while Yao et al. (2015) use 0.0025 s).

2.1. Synthetic waveforms

We calculate the Green's function for the 1D reference Earth model (PREM) by generalized ray theory (Helmberger 1983) and convolve it with Gaussian source time functions to generate synthetic seismograms with a sampling interval of 0.001 s. Waveforms are then decimated to a sampling interval of 0.01 s to make them more comparable to real records. All the synthetic waveforms are filtered with the worldwide standard seismic network short-period (WWSSN-SP) instrument response which leaves a dominant frequency between 1 and 1.5 Hz, as is standard practice in studies of inner core secular variation (Fig. 1b). We generate synthetic seismograms with time shifts of 0.005 s, 0.02 s, 0.01 s and 0.05 s, for sampling intervals of 0.001 s and 0.01 s.

2.2. Real waveforms

We use the catalogue of earthquake doublets compiled by Yao et al. (2015) and extract ten representative waveform pairs from six earthquake doublets (Table 1, Fig. 2). The relative location, depth and origin time between doublets is corrected for using the master event algorithm outlined in Wen (2006) and Yao et al. (2015). Waveforms are filtered with the WWSSN-SP instrument response and the arrival time of inner core phases is firstly hand-picked (Fig. 2). The relative arrival time of inner core phases between doublets is then calculated by cross-correlation of the waveforms.

The stations used are broadband stations from the Global Seismographic Network (II), the Kyrgyz Seismic Telemetry Network (KN), and the New China Digital Seismograph Network (IC) (Table 1). Stations have a sampling rate of 20 Hz (0.05 s sampling interval) except for network KN which has a sampling rate of 40 Hz. Data must therefore be interpolated to a smaller sampling interval for high resolution measurements. We interpolate data to sampling rates of 0.01 s and 0.001 s using the Wiggins (1976) interpolation algorithm implemented in the Seismic Analysis Code (SAC). There are numerous digital interpolation algorithms and we do not attempt to compare them here.

3. Results

Our synthetic waveform tests show that the largest errors in time shifts occur when time shifts are less than the sampling rate as expected, but there are errors in the calculated time shift even when the time shift is larger than the sampling interval (Fig. 3). The 'cc_sac' and MATLAB algorithms give results to the nearest sample, whereas 'sac_wfcc' undertakes further interpolation – this means that using 'sac_wfcc' gives smaller errors but it also never calculates the exact result. The largest errors calculated in the simple synthetic data tests are 0.002 s for sampling rate of 0.001 s and 0.005 s for sampling rate of 0.01 s (Fig. 3) – these errors are likely a significant underestimate of true errors in real data as subsequently analysed.

The variation in differential time (dt) for each of the ten waveform pairs for different cross-correlation algorithms and window lengths is shown in Fig. 4. The double differential time (ddt) between two phases of a doublet is often used to eliminate origin time and clock errors, since the common errors cancel out. The differential time (dt) and double differential time (ddt) between doublets is calculated as:

$$dt(PKiKP) = t(PKiKP)_2 - t(PKiKP)_1 \tag{1}$$

$$dt(PKIKP) = t(PKIKP)_2 - t(PKIKP)_1 \tag{2}$$

$$ddt(PKiKP - PKIKP) = dt(PKiKP) - dt(PKIKP), \tag{3}$$

where the subscript corresponds to the doublet event and t is the arrival time. The average range (difference between the largest and smallest values) for the calculated PKIKP and PKiKP differential times is 0.01 s (Table 2). In general, the varying window length has a larger effect on the differential time than the cross-correlation algorithm (Fig. 4), principally because seismic waves at different arrival times could have different travel time changes. We expect the cross-correlation algorithms to produce the same results, except for small numerical errors. The differences between the algorithms is likely due to differences in data processing built into the algorithms, for example applying a taper before the Fourier Transform. Waveform pair number 8 shows the largest difference between algorithms. To investigate the origin of this difference, we remove the data tapering used in the 'cc_sac' code and find that when no tapering is applied, the result is the same as the time-domain MATLAB implementation. The lower frequency content of waveform pair number 8 (it is further filtered from 0.5–1 Hz to remove high frequency noise) may explain why it has the largest range in values, since we expect resolution to scale with frequency. The range for the double differential time varies from 0.01 s to 0.04 s, with an average of

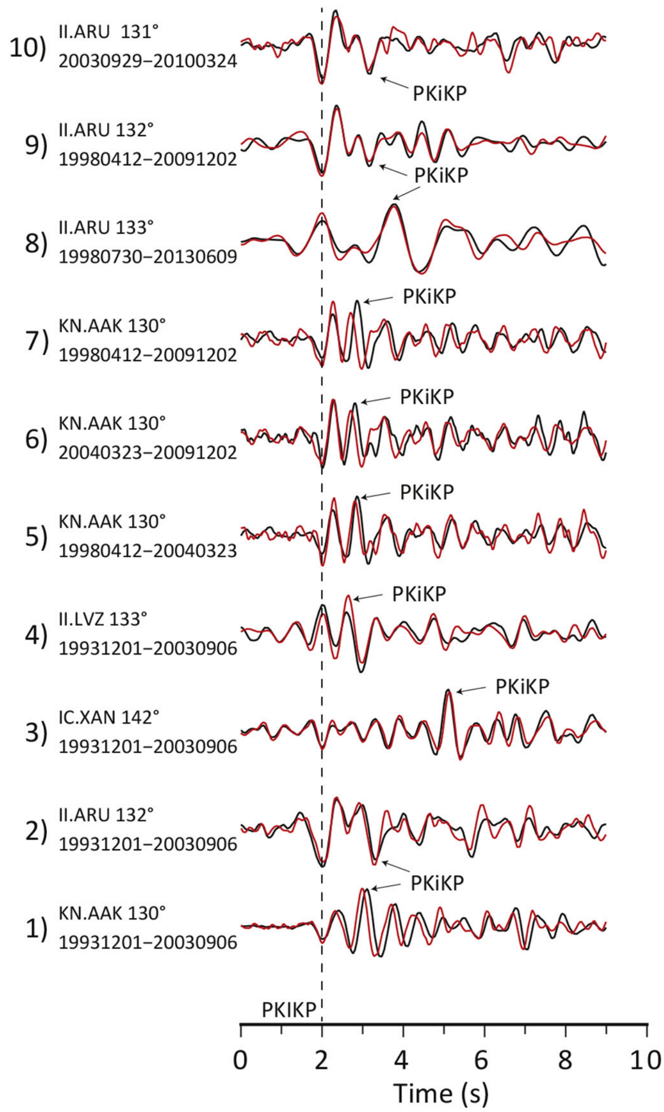


Fig. 2. Waveforms of the ten waveforms pairs we study here (earlier event: black traces; later events: red traces) for six earthquake doublets as listed in Table 1 with hand-picked PKIKP arrival aligned at 2 s and corresponding PKiKP picks labelled. All waveforms are convolved with the WWSSN-SP instrument response and waveform pair number 8 is further filtered from 0.5–1 Hz. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.02 s (Fig. 4). This magnitude is similar for sampling rates of 0.001 s and 0.01 s, although the exact values are different (Fig. S1, S2). We therefore conclude that the uncertainty related to the cross-correlation measurements is 0.01 s for differential times and 0.02 s for double differential times.

We investigate two waveform pairs in more detail by comparing the results from both Yang and Song (2020a) and Yao et al. (2015). These are the waveform pairs numbered 1 and 2 in Table 1 for the doublet earthquakes on 1/12/1993 and 6/9/2003. The waveforms are shown in Fig. 5a. We replicate the data processing used in each study by convolving with the WWSSN-SP instrument response and additionally bandpass filtering from 0.6–3 Hz for Yang and Song (2020a). We also replicate the PKIKP and PKiKP picks from each study as closely as possible. It is difficult to pick the onset times of PKIKP and PKiKP for these waveforms and the picks differ between studies so that different parts of the waveform are defined as PKIKP and PKiKP. The window lengths also vary between studies - 0.8 s and 1 s for Yao et al. (2015) and Yang and Song (2020a) respectively. Overall, we find that ddt(PKiKP-PKIKP) varies by only 0.01 s between the two studies using the same cross-correlation algorithm (Fig. 5b). However, there is a larger variation in both dt(PKIKP) and dt(PKiKP) of up to 0.06 s (Fig. 5b). Although the double differential times are similar, the magnitude of the individual differential times is still important since it governs how the signal is interpreted (i.e. whether the change originates from the ICB or within the inner core's interior and if a rotation rate is inferred, what that rotation rate is). This shows how the details of the defined onset time, window length and prior signal processing influence the measured time shifts.

We compare our measured uncertainty to the largest published datasets of PKIKP and PKiKP differential times from earthquake doublets (Yang and Song 2020a). Yang and Song (2020a) form double differential times using SKP as a reference seismic phase to try to minimise the influence of earthquake location and origin time errors, although this method is hotly debated (Yao et al. 2020; Yang and Song 2020c). We

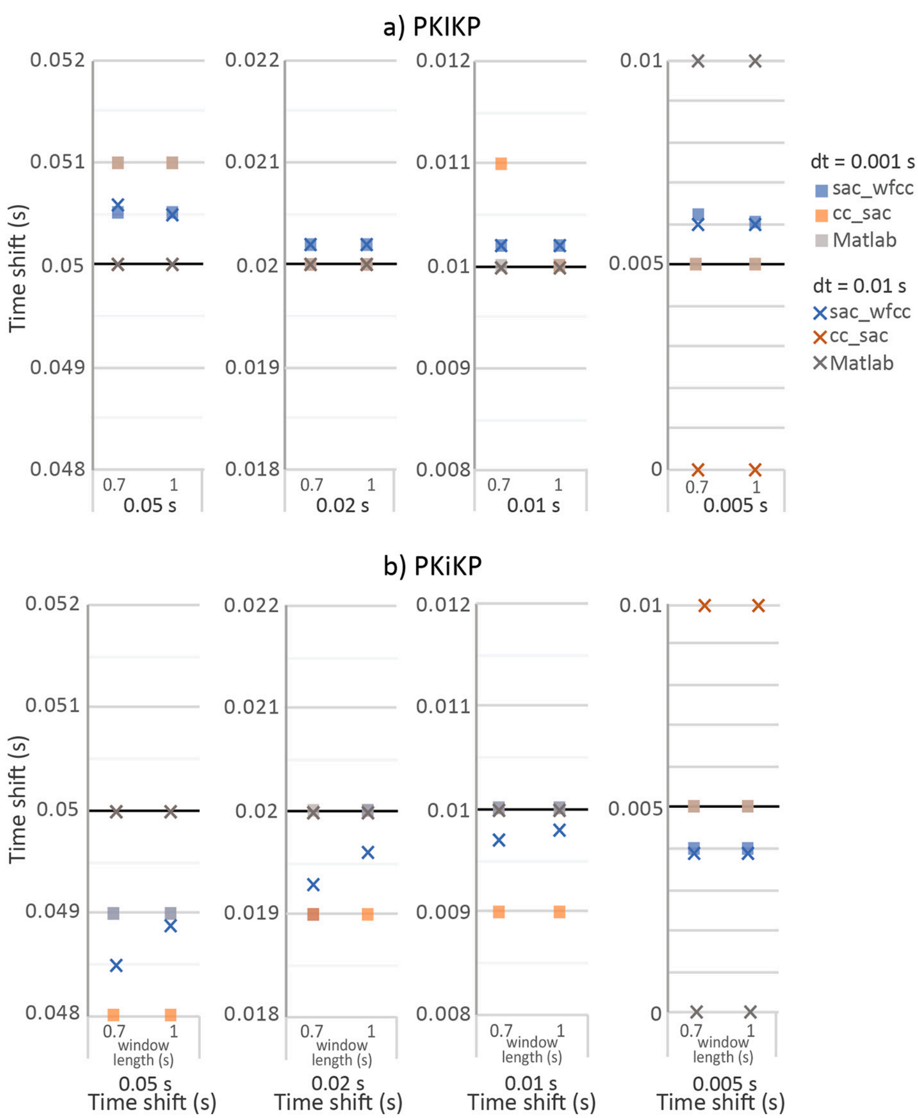


Fig. 3. Time shifts measured by cross-correlation of synthetic waveforms generated with a known time shift for a) PKIKP and b) PKiKP. Generated time shifts are shown in each panel, from left to right: 0.05 s, 0.02 s, 0.01 s and 0.005 s. Results are shown for different cross-correlation algorithms 'sac_wfcc' (blue), 'cc_sac' (orange) and Matlab time domain (grey) and for sampling intervals of 0.001 s (squares) and waveforms decimated to 0.01 s (crosses). The results overlaps in several cases (where there are fewer than 6 measurements in each panel), causing a blending of colours. The used time windows are 0.7 s and 1 s, centred at the arrival time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

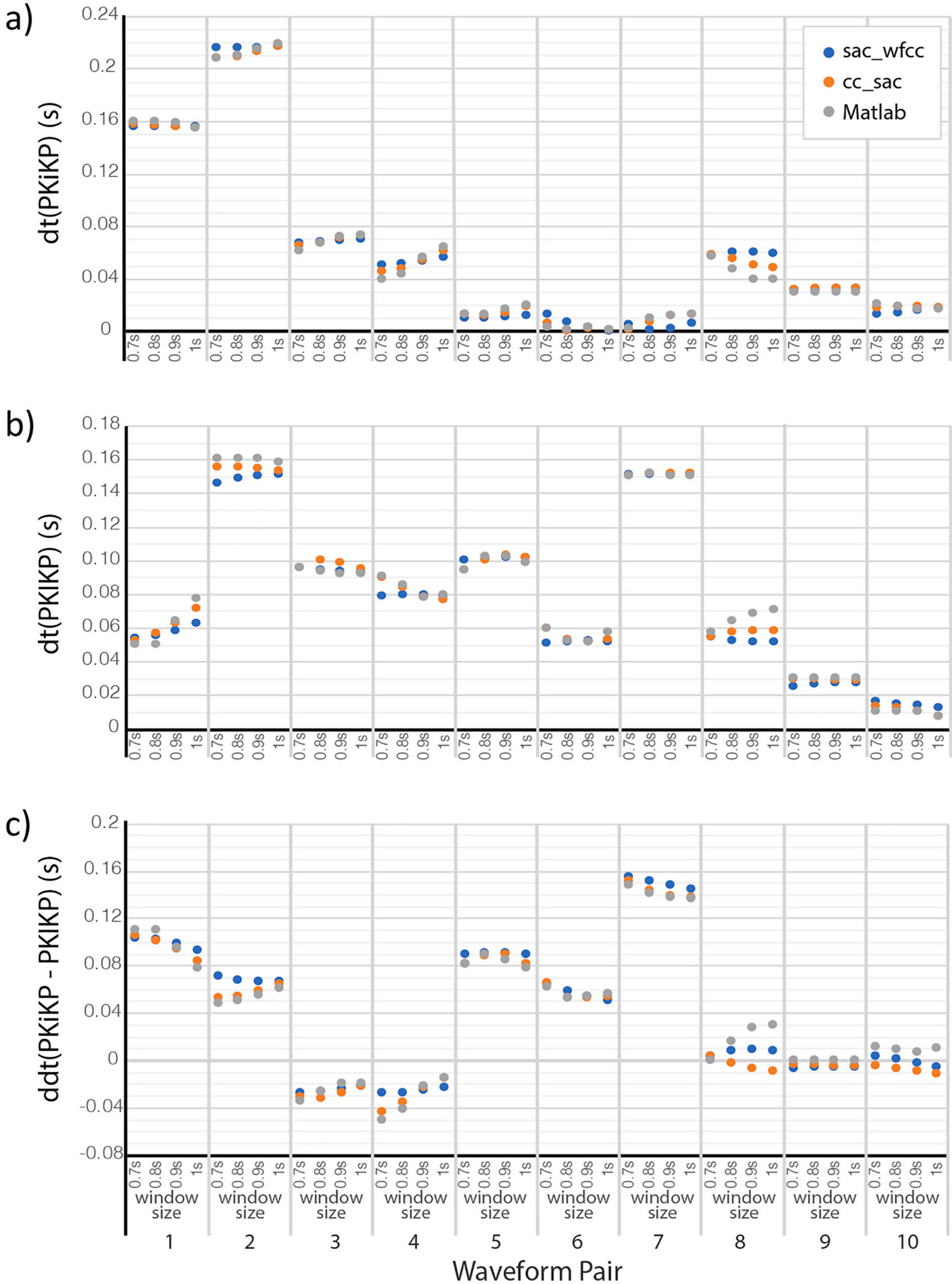


Fig. 4. Differential times for a) PKiKP, b) PKIKP and c) PKiKP-PKIKP for ten waveform pairs, calculated using different cross-correlation algorithms (colours) and window lengths (x-axis). Data is interpolated to a sampling rate of 0.001 s. Waveform pair number corresponds the pairs listed in Table 1.

Table 2
Variation in differential time phases.

Differential travel time phase	Average standard deviation (s)	Average range (s)
Sampling rate 0.001 s		
dt(PKiKP)	0.004	0.011
dt(PKIKP)	0.004	0.013
ddt(PKiKP – PKIKP)	0.007	0.023
Sampling rate 0.01 s		
dt(PKiKP)	0.004	0.01
dt(PKIKP)	0.004	0.01
ddt(PKiKP – PKIKP)	0.007	0.02

reproduce their results in Fig. 6, with the addition of our calculated measurement resolution. We find that most data are below the resolution threshold. Assuming a measurement uncertainty of 0.02 s as calculated here, 80% of the data is below the resolution. Reducing the uncertainty to 0.01 s still results in 58% of data being below this value. The conclusion of Yang and Song (2020a), that temporal variations in inner core phases originate from the inner core's interior due to rigid body rotation, is based on a statistical analysis of their data. Fig. 6 shows their fitted trend lines which indicate that temporal changes are larger for and originate at the PKIKP phase instead of the PKiKP phase. However, when 80% of the data that is below measurement resolution is excluded, the fitted trendlines are much less statistically significant. *Re*-assessment of the mechanism responsible for observed temporal changes in inner core phases is therefore warranted.

We note that additional factors and uncertainties need to be accounted for to study temporal change of inner core properties using earthquake doublets, such as i) relative location and origin time between earthquake doublets, ii) doublet relocation error, iii) mantle heterogeneity due to the small path difference in the mantle, iv) waveform complexities such as phase overlaps, scattering and diffractions. There is also uncertainty in the arrival time of PKIKP and PKiKP as demonstrated in the varying polarity between the two phases in Fig. 2 and the differing pick times between two studies shown in Fig. 5. PKiKP is expected to have the opposite polarity to PKIKP, due to the predicted phase shift of nearly 180°. However in some cases, PKiKP is picked with the same polarity as PKIKP (for example waveform pair numbers 2,4,8,9,10 in Fig. 2). The same polarity between the phases likely indicates interference between PKiKP and diffractions from the ICB, although further waveform modelling is needed to verify this.

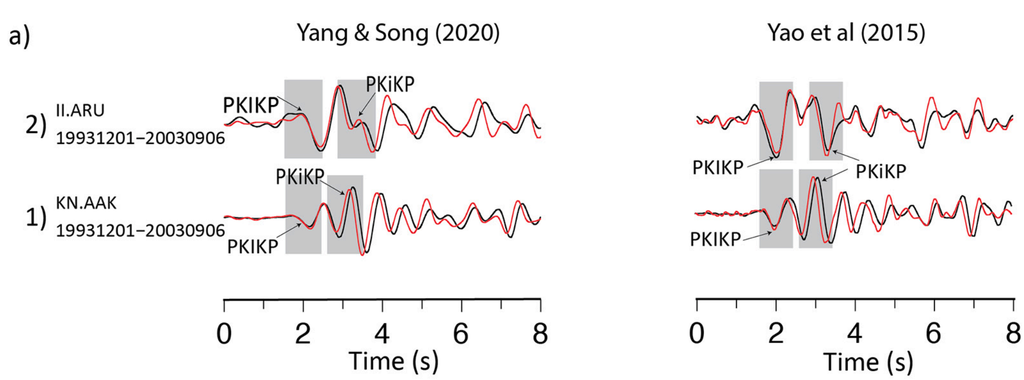
An alternative estimate of measurement uncertainty in core phase differential times is provided in the studies of Iritani et al. (2010) and Garcia et al. (2006) which fit inner core waveforms with synthetics via simulated annealing algorithms. While the studies are focused on inner core attenuation, they do provide a large dataset displaying scatter in differential time measurements. Garcia et al. (2006) estimate differential time measurement errors on the order of 0.1–0.5 s, while scatter in the large dataset of Iritani et al. (2010) indicate measurement errors on the order of 0.2 s. These large errors reflect waveform complexities that are not modelled in synthetic data such as depth phases, complex source time functions and diffracted wave arrivals. Since we use earthquake doublets which have highly similar source characteristics and are in approximately the same location, uncertainties arising from source factors should be minimised. Nevertheless, we anticipate that the uncertainties we derive here may be on the low end of the true uncertainty.

4. Conclusions

We show that it is important to consider the uncertainty related to cross-correlation when measuring temporal changes in inner core seismic waves. Details related to the data processing, window length, pick time, tapering applied within cross-correlation algorithms and sampling rate all affect the calculated time shift. We calculate uncertainties of 0.01 s and 0.02 s for differential times and double differential times respectively. The uncertainty is of a similar magnitude to reported double differential times of PKIKP and PKiKP phases, and 80% of values in a recent study (Yang and Song 2020a) fall below the measurement resolution. We suggest that future studies account for the measurement uncertainties we calculate here when interpreting temporal changes in inner core travel times and that a re-assessment of the mechanism responsible for the observed temporal changes is warranted.

Declaration of Competing Interest

The authors declare that they have no known competing financial



b)

Author	Waveform Pair	Station	Data 1 Date	Data 2 Date	dt(PKIKP) (s)	dt(PKiKP) (s)	ddt(PKiKP-PKIKP) (s)
Yang & Song 2020	1	AAK	1/12/1993	6/9/2003	0.05	0.15	**0.10**
Yao et al 2015					0.05	0.16	**0.11**
Yang & Song 2020	2	ARU	1/12/1993	6/9/2003	0.10	0.15	**0.05**
Yao et al 2015					0.16	0.21	**0.05**

Fig. 5. a) Comparison of waveforms and time windows (shaded boxes) used in Yang and Song (2020) and Yao et al. (2015) for two waveform pairs. Waveforms are aligned on the PKIKP arrival. b) Comparison of cross-correlation derived differential times from waveforms in Yang and Song (2020) (time window: 1 s) and waveforms in Yao et al. (2015) (time window: 0.8 s). Cross-correlations were calculated using the MATLAB time domain algorithm with a sampling rate of 0.01 s. Earthquake origin time is set to be the same between the studies.

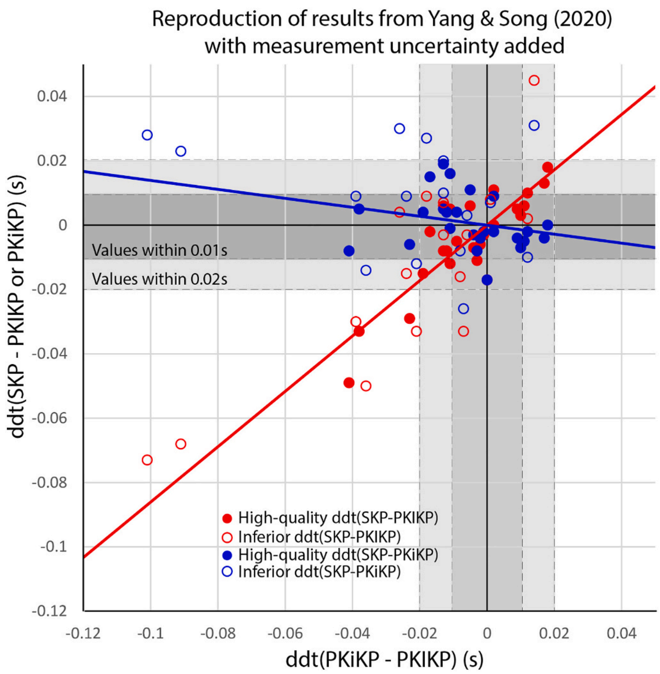


Fig. 6. Reproduction of Fig. 6 from Yang and Song (2020) with measurement uncertainty added (shaded grey boxes).

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We use Taup (Crotwell et al. 1999) and GMT (Wessel et al. 2013). The cc_sac code is freely available at https://github.com/core-man/repeating-earthquake and uses the FFTW subroutine library (www.fftw.org). We thank Dr. Lupei Zhu who wrote the sac_wfcc code and Dr. Zhigang Peng who makes the code available for downloaded at http://geophysics.eas.gatech.edu/people/zpeng/Teaching/SAC_Tutorial. Matlab xcorrFD (cross-correlation in frequency domain) is obtained from MATLAB central file exchange (retrieved 4th August 2020). We thank the editor Vernon Cormier and two anonymous reviewers for constructive feedback that improved the article. We thank Michael Braim for the original inspiration to undertake this work. This is Earth Observatory of Singapore contribution number 334. This work is supported by a Nanyang Presidential Postdoctoral Fellowship awarded to K. L. (No. 04INS000845A620). CRediT author statement - K.L.: Conceptualisation, Investigation, Supervision, Writing; M.I. Investigation, Visualisation, Writing; J.Y.: Data curation, Software, Writing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pepi.2020.106606.

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