Nature of inner-core temporal changes and a precise estimate of differential inner-core rotation rate

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PART A: Nature of inner-core temporal changes

Summary:

- Temporal changes of inner-core seismic waves over several years have been well well established from high-quality repeating earthquakes.
- The temporal changes mostly originate from the interior, rather than the boundary, of the inner core.
- We believe inner core rotation (see part B for the rate estimation) still provides the most plausible interpretation.

PART B: Precise estimate of inner-core rotation rate

Summary:

- We found direct evidence for the differential rotation of the inner core using repeating earthquakes of the South Sandwich Islands (SSI) and twin stations (AAK and KZA) in Kyrgyzstan.
- From the new observations, the rate of the rotation can be accurately determined as ~0.13° per year eastward from 1991 to 2010.

(click here to PART B directly)

PART A: **Nature of inner-core temporal changes**

Decadal variability of IC seismic waves from repeating earthquakes

The strongest confirmation of the IC temporal change comes from repeating earthquakes (doublets), where the non-IC phases are identical and IC phases change over several years.

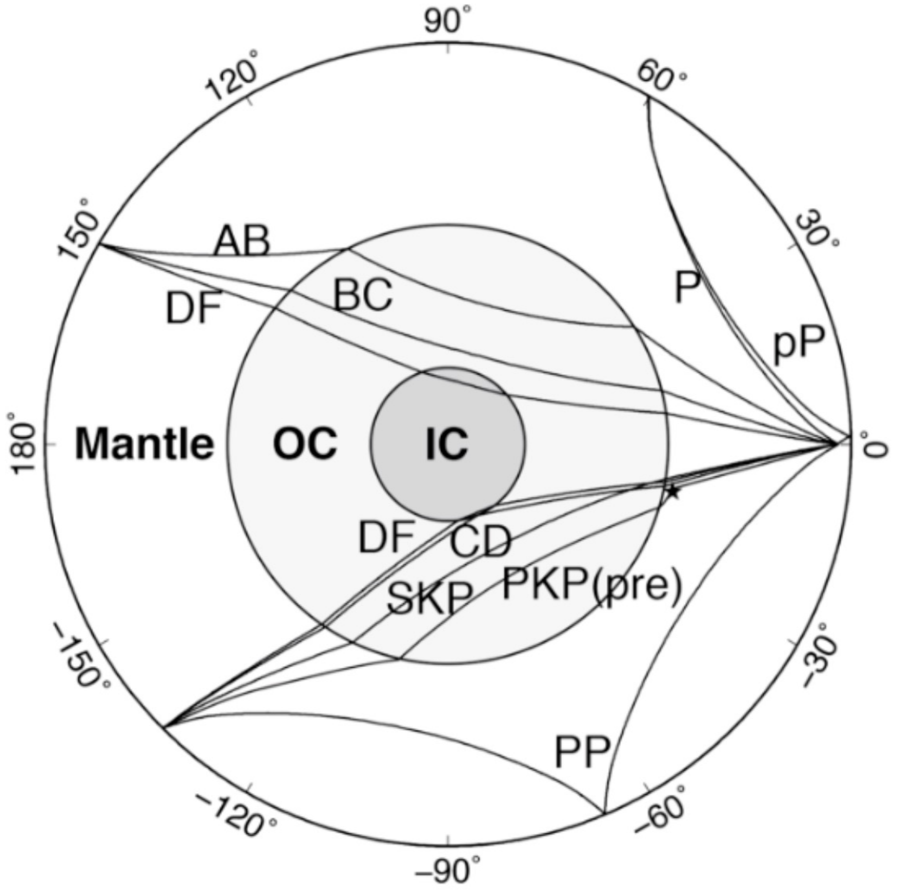


Figure 1. Seismic phases used in this study.

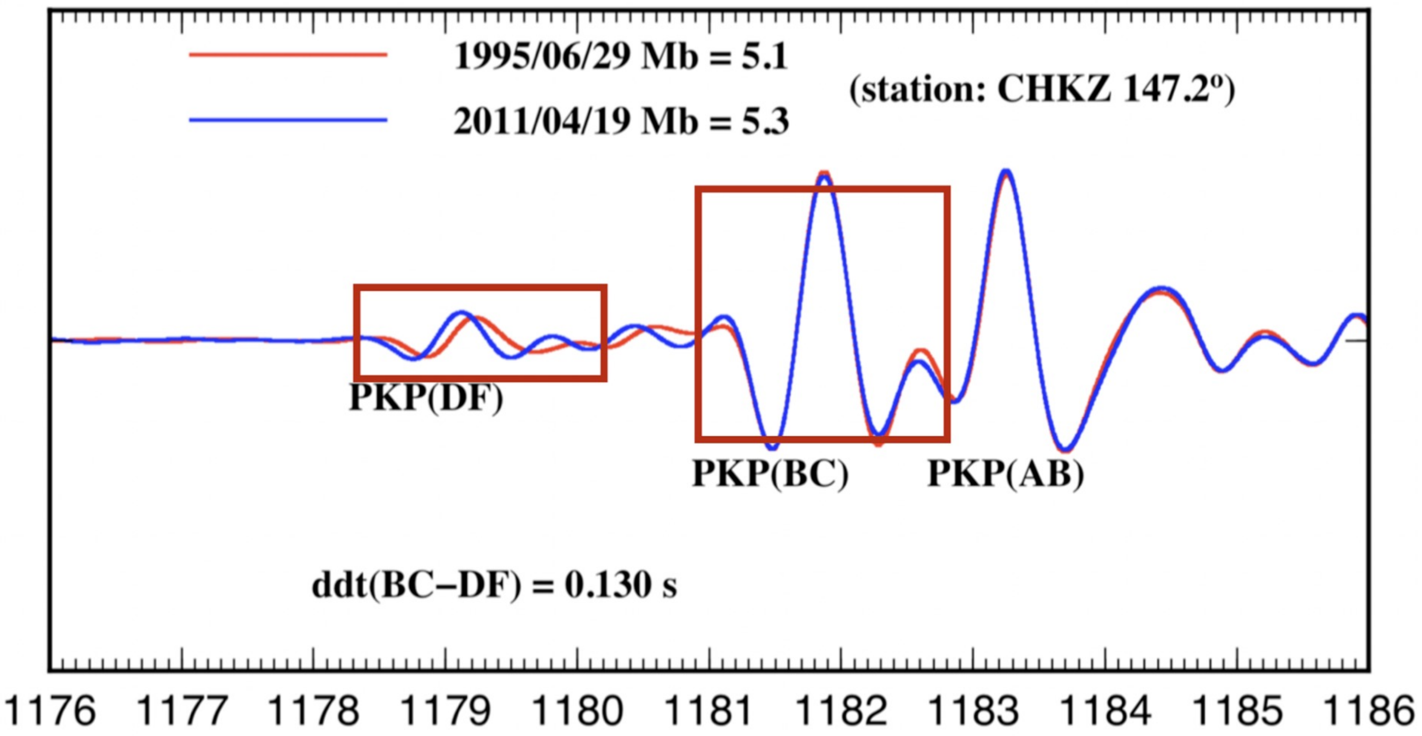
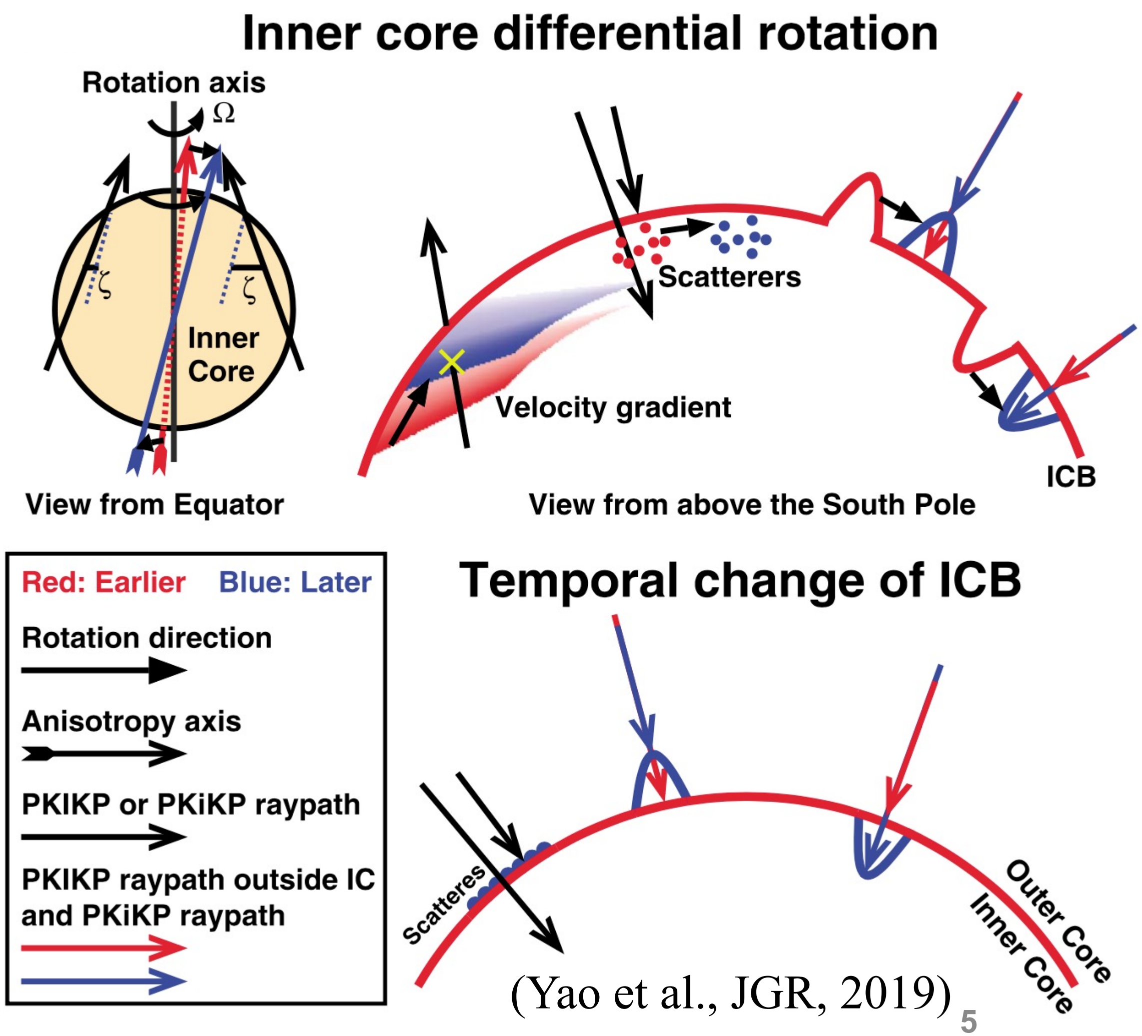


Figure 2. Example of temporal changes of DF from a high-quality doublet.

Debate on its origin - IC rotation or changes of the ICB

There are two competing models of the temporal changes:
(1) From the body of the inner core, preferably from the IC rotation shifting its **interior** heterogeneities (Creager, 1997; Vidale et al., 2000; Zhang et al., 2005; etc.)
(2) Solely from rapid and localized changes of the IC **surface** (Wen, 2006; Yao et al., 2015, 2019; etc.)

Both cannot be valid. Debating the issues is important to understand the mechanism of the IC changes in particular and the evolution and dynamics of the earth's core in general.



(Yao et al., JGR, 2019)

Origin mostly from IC's interior instead of surface

Key assumption:
If the temporal changes are mostly from the IC surface, the CD phase (reflecting from the IC surface) should exhibit stronger temporal changes than the DF phase (refracting inside the IC interior).

Key question: Which phase (**CD or DF**) shows stronger temporal changes?

Data and method:
(1) We used high-quality doublets to study the temporal changes of DF and CD, at the distance range between 128° and 142° (where they coexist and are well separated), and analyzed which phase has stronger temporal change.
(2) We used non-IC phase (mostly SKP) as reference to form double differential time (ddt) between two phases and two events of a doublet, e.g.,
ddt(SKP-DF) = dt(SKP) - dt(DF) = $(T(SKP_2)-T(SKP_1)) - (T(DF_2)-T(DF_1))$.

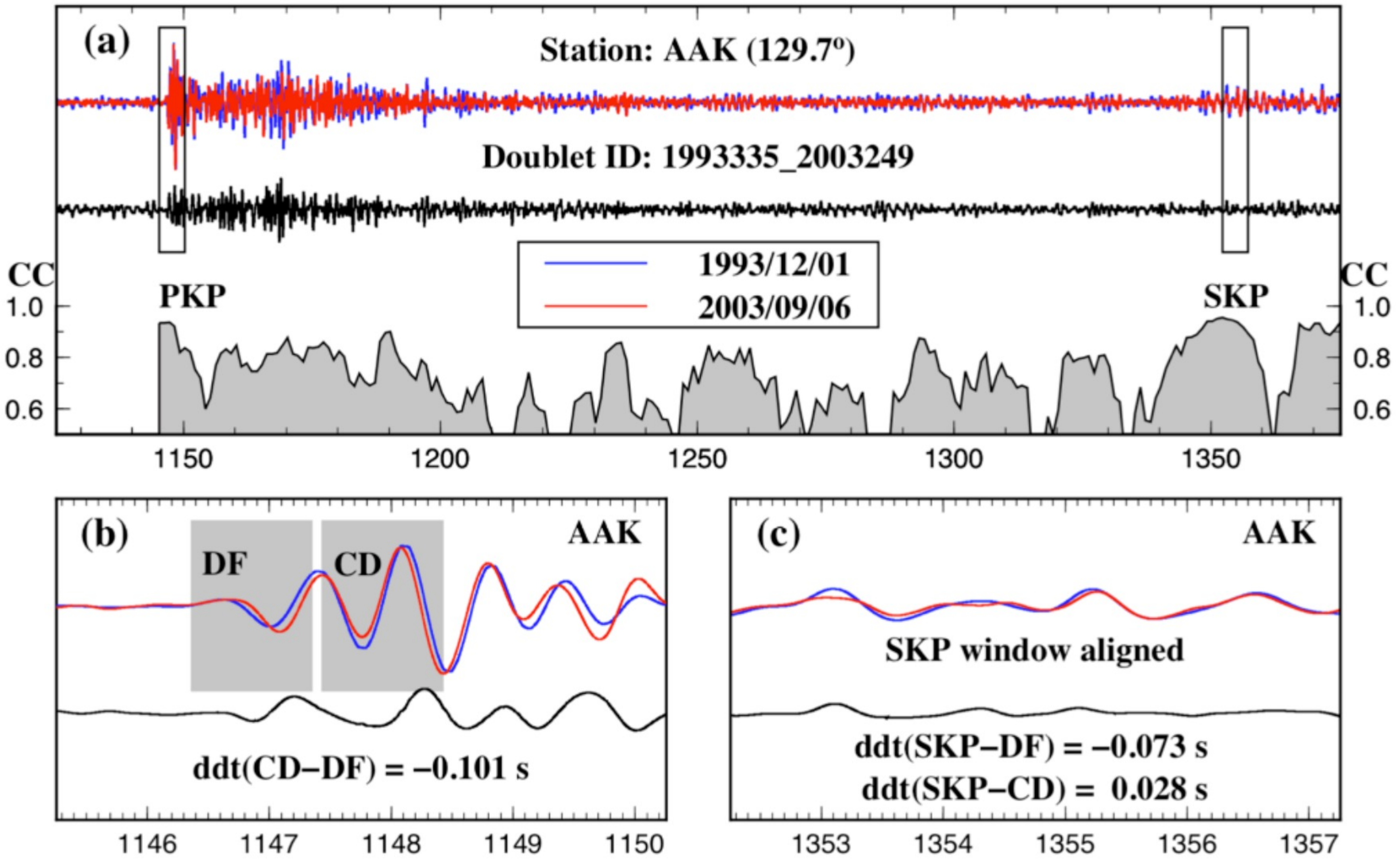
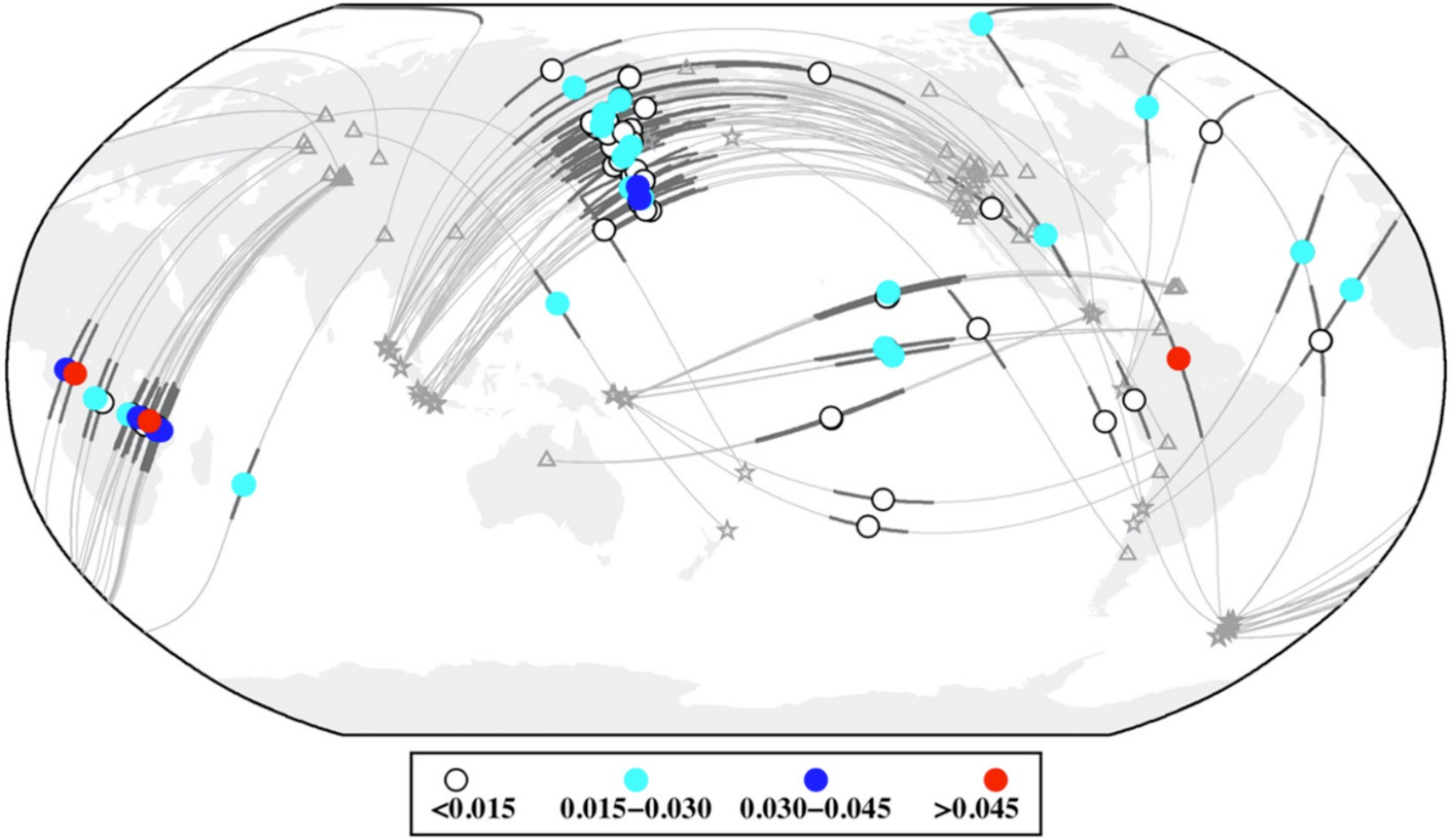


Figure 3. Temporal changes of DF and CD waveforms sampled by a doublet of South Sandwich Islands (SSI) to station AAK. The waveforms are aligned by the SKP phase. The black traces are the waveform differences between the old (blue) and new (red) repeaters.

Observations: temporal changes, if any, are mostly from DF rather than CD

- Note that ddt(SKP-DF) is nearly 3 times of ddt(SKP-CD) and obvious waveform changes start from DF.
- Previous studies using absolute time to identify temporal changes of CD (Wen, 2006 Science; Yao et al; 2015, 2019 JGR) are not reliable due to **frequent clock drifts (see** **page 9****)**, especially in 1990s.

Figure 4. Map of ddt(CD-DF) measurements (circles) from doublets (stars) to stations (triangles).



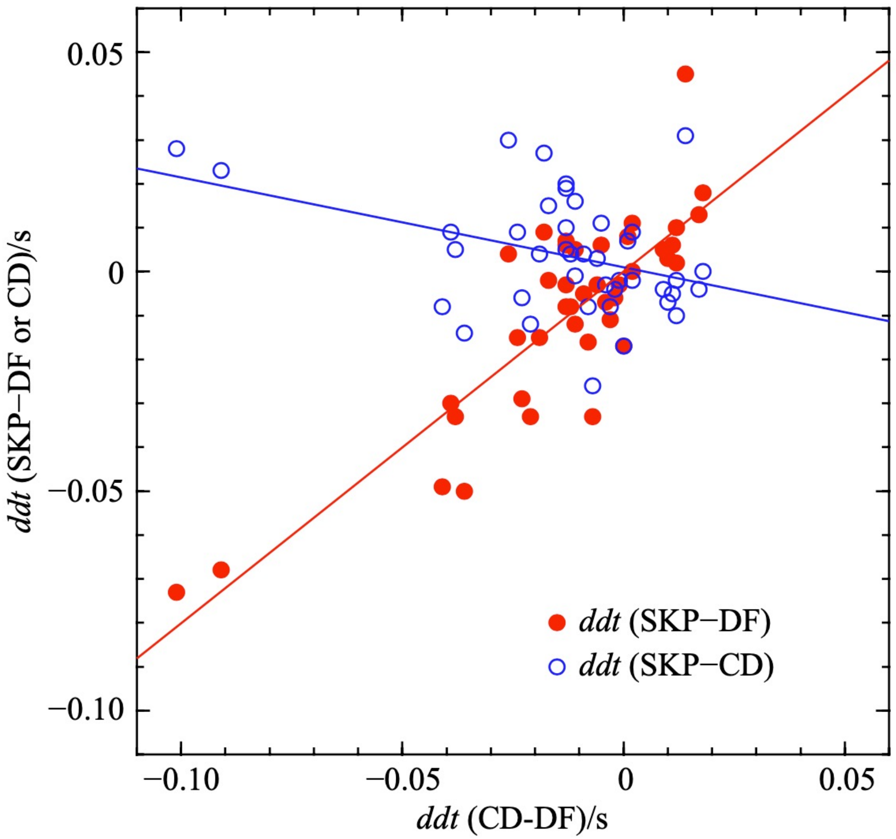


Figure 5. The double differential time ddt(CD-DF) vs ddt(SKP-CD) (blue) or ddt(SKP-DF) (red)

Considering the measurement error of ~0.02 s (Yang & Song, EPSL, 2020; Lithgoe et al., PEPI, 2020), none of the ddt(SKP-CD) are significantly non-zero, but some ddt(SKP-DF) measurements are highly significant.

Observations of clock errors

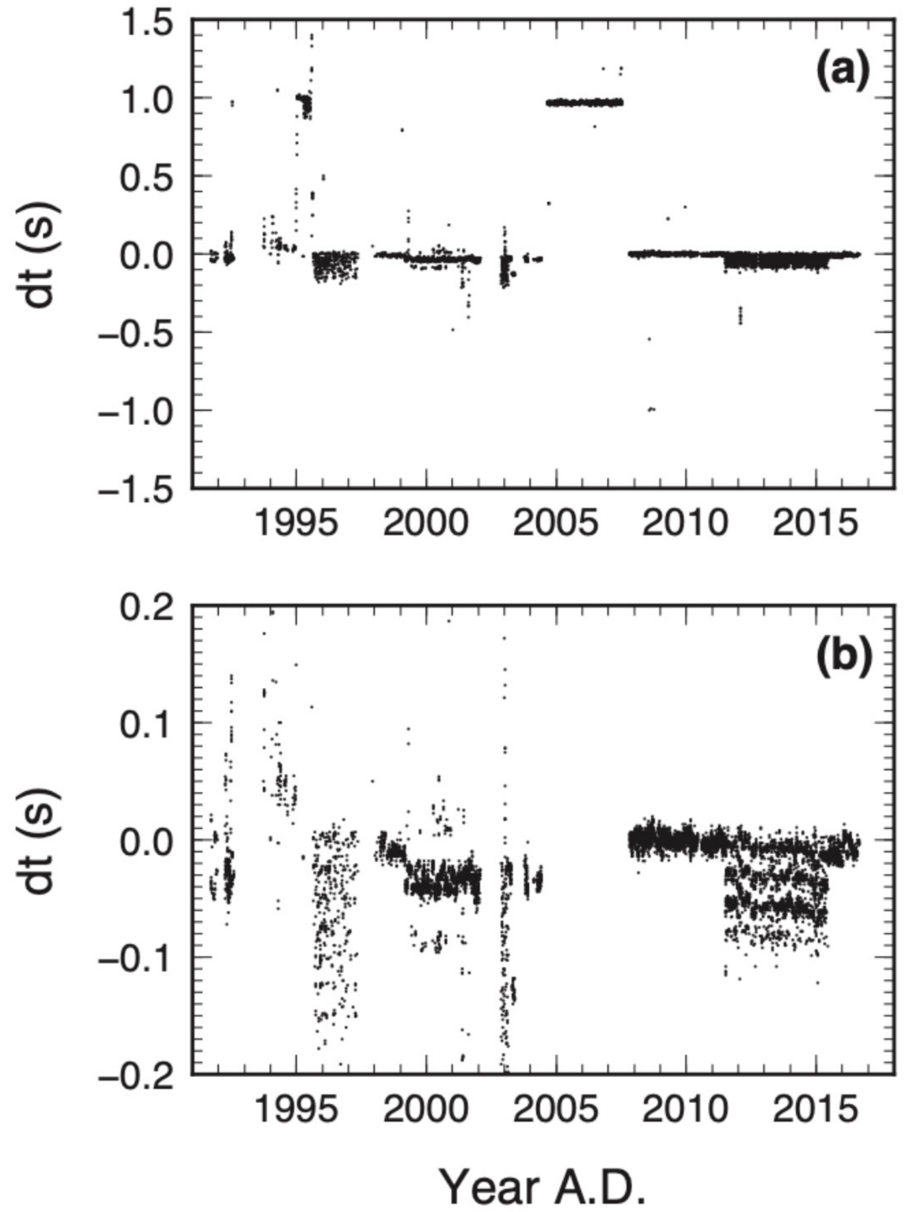
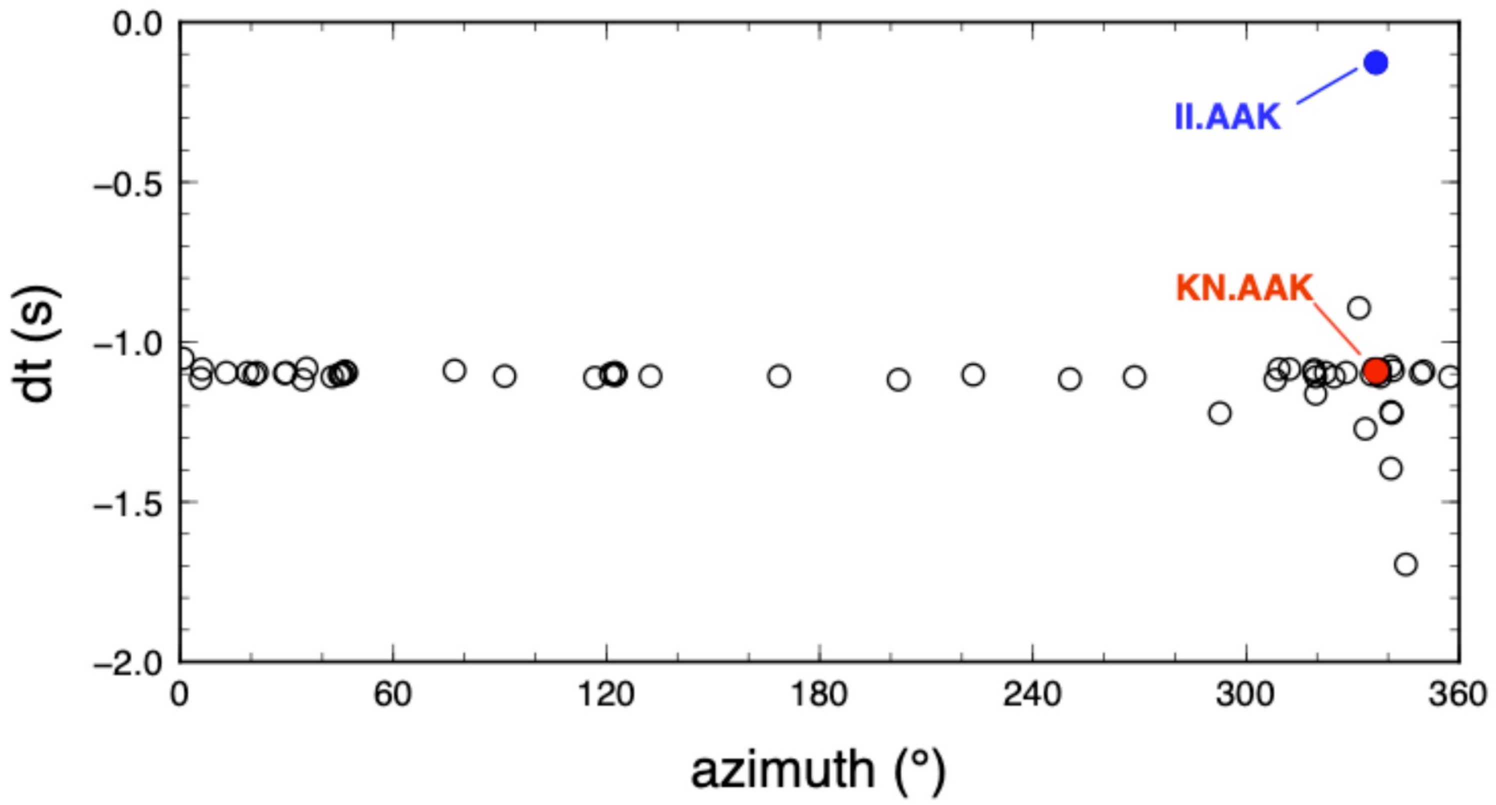


Figure 6. The arrival time difference (dt) between stations II.AAK (GSN) and KN.AAK (KNET) from the same event as a function of the event origin time. The two stations are nearly collocated, and their records are nearly identical. (b) is an enlarged view of (a). The time shifts are computed from cross-correlations.

The comparison of arrival times of two nearly collocated stations (II.AAK and KN.AAK) indicate either or both stations have frequent clock errors (data points deviating from zero in Fig. 6).



Clock errors up to 1 s at station II.AAK and many other stations.

Figure 7. Relative time (dt) measurements from a high-quality doublet vs azimuth to the recording stations. The doublet is in 2005 and 2009 from Yang and Song (2020a). The dt is T(2009)-T(2005) at the same station. The GSN station II.AAK shows obvious clock errors, as an outlier away from the nearly constant value of most stations, while the KN.AAK agrees with the constant value.

PART B: Precise estimate of inner-core rotation rate

A fortuitous geometry of events and stations

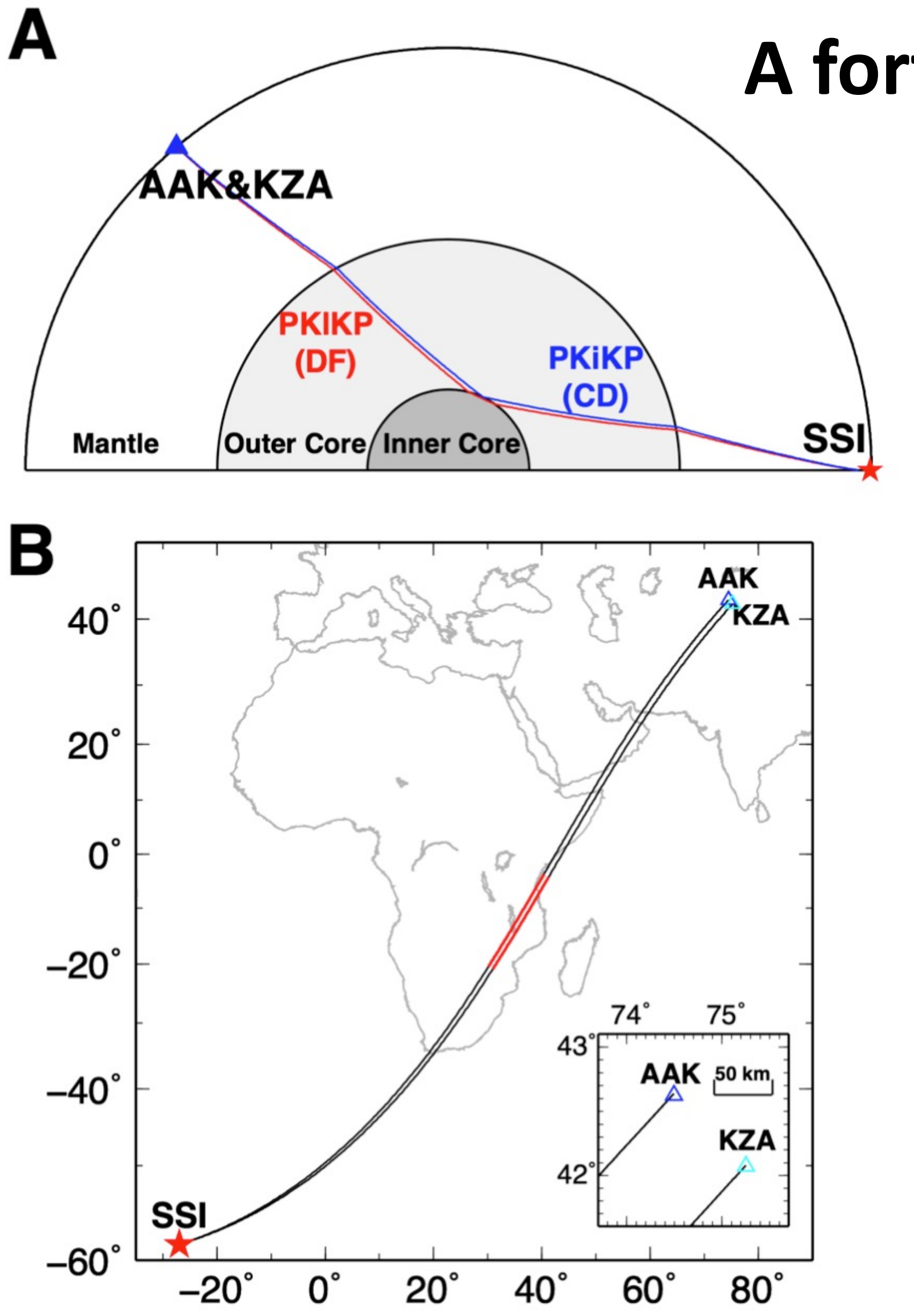
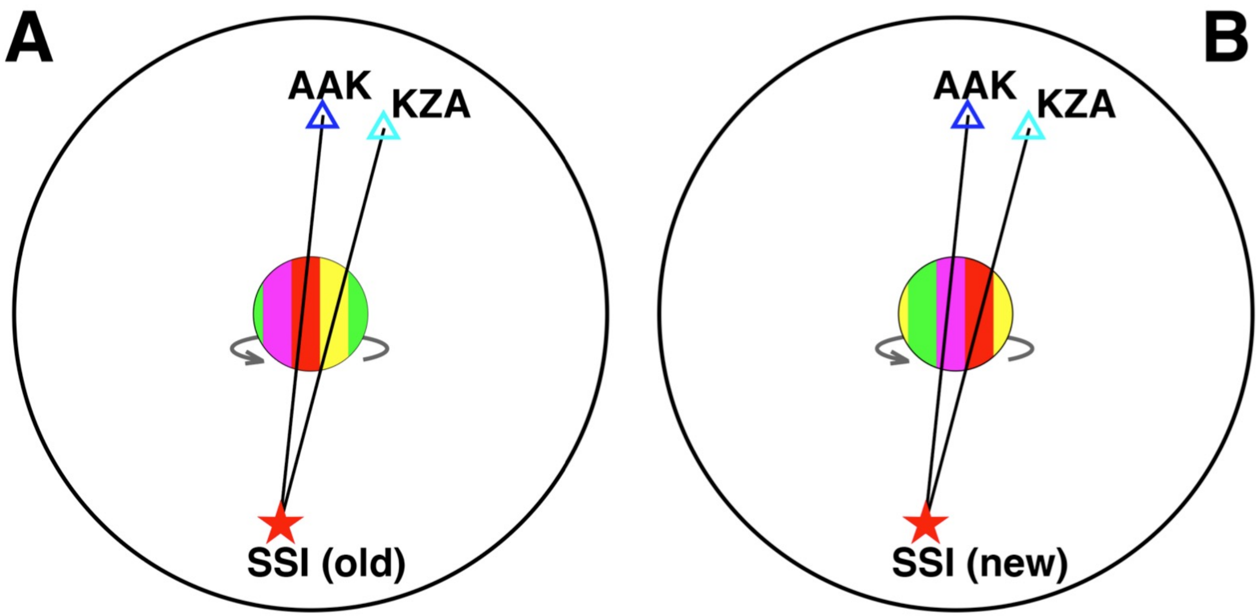


Figure 8. Ray paths of IC reflective PKiKP (CD, blue) and refractive PKIKP (DF, red) waves (A) and their surface projections (B). In B, the red part of the raypath represents the PKIKP wave leg traversing the IC.

Twin stations AAK and KZA are peculiarly located that are nearly **equidistant** (differ by 0.01 degree only) to the SSI doublets.

Key ideas:

Under the assumption of IC super-rotation (eastward, faster than the whole earth), the IC structure sampled by station AAK could be captured by a later repeater to station KZA at the right time lapse.



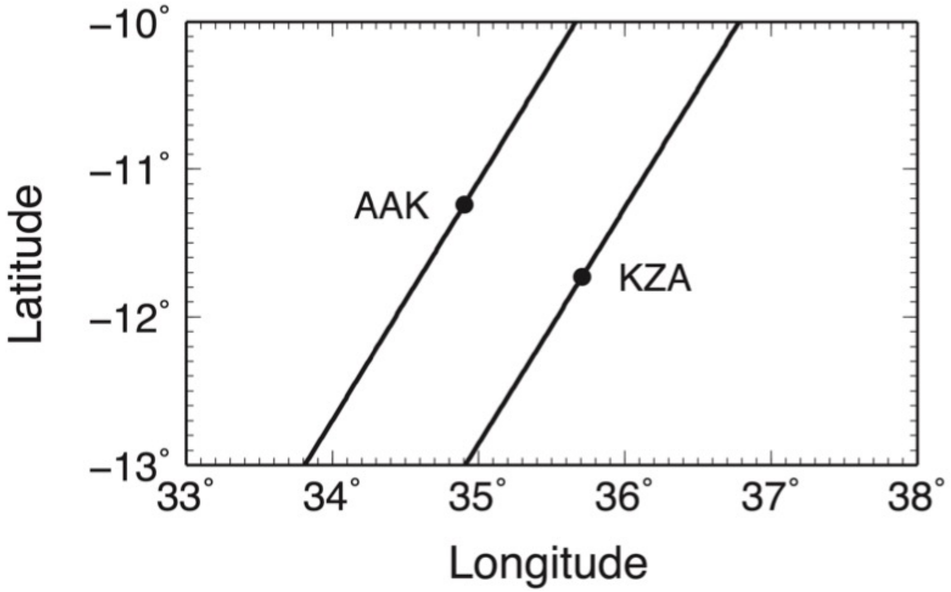


Figure 9. Cartoon of the eastward rotating and laterally varying IC captured by the twin stations and a pair of SSI repeating events. Note that the location difference between the two stations and the amount of the IC rotation are greatly exaggerated to show the same IC structure that was sampled by the old event to AAK was later captured by the new event to KZA.

Figure 10. Enlarged map view of the partial ray segments in the IC from an example SSI event to the twin stations. The black dots represent the bottoming points of the DF rays, with longitudinal separation of ~0.8° .

Rate estimation from the match of waveforms

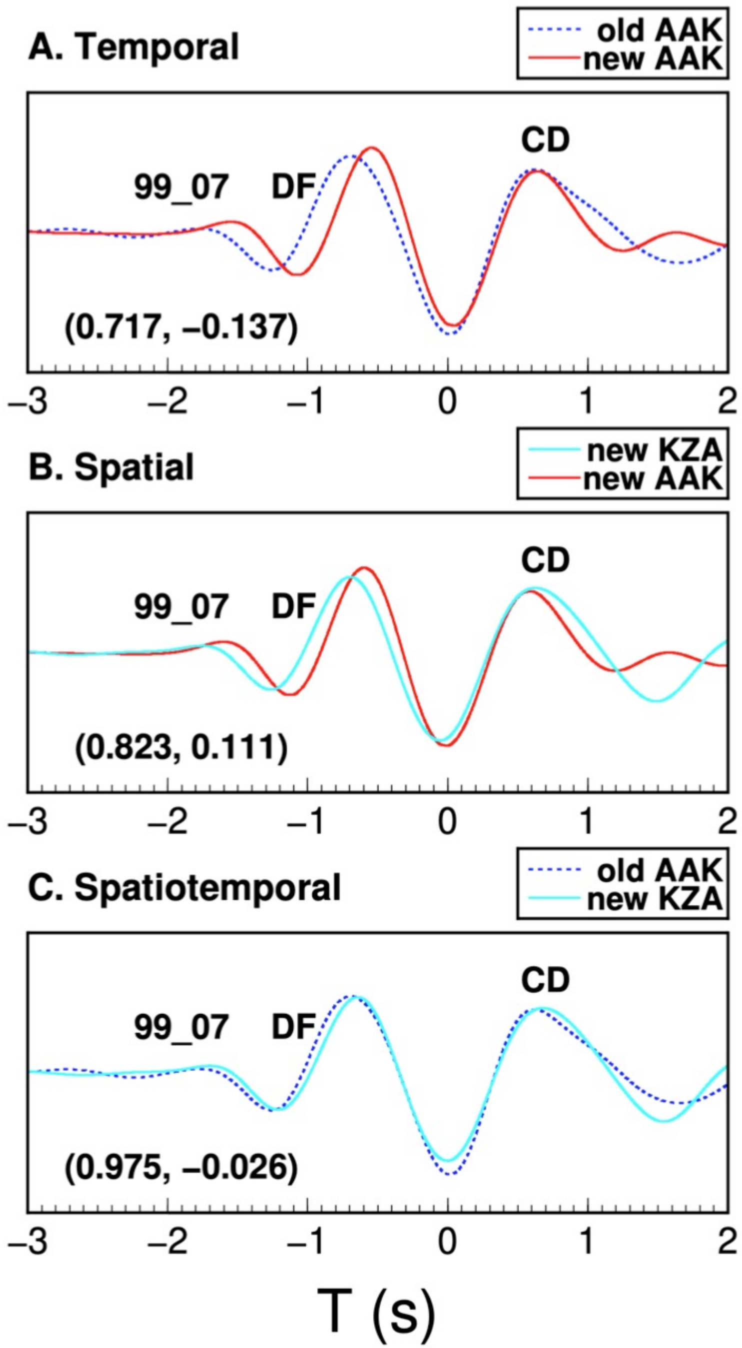


Figure 11. Waveform comparisons from an SSI doublet (ID 99_07, with events in 1999 and 2007 and lapse of 7.2 years) to the twin stations. (A) Temporal change recorded by AAK. (B) Spatial variation sampled by the new (later) event to the twin stations. (C) Waveform comparison between the old (earlier) event to station AAK and the new event to station KZA. The waveforms are aligned by CD at 0 time using cross-correlation and are normalized by their peak amplitudes. Cross-correlation coefficient of DF at the zero lag and time shift of DF (ddt in seconds) from the best cross-correlation are labeled in the parentheses.

When the IC rotates eastward by ~0.8° , the structure sampled by the AAK path would be sampled by the KZA path at a later time, allowing us to determine accurately the rotation rate.

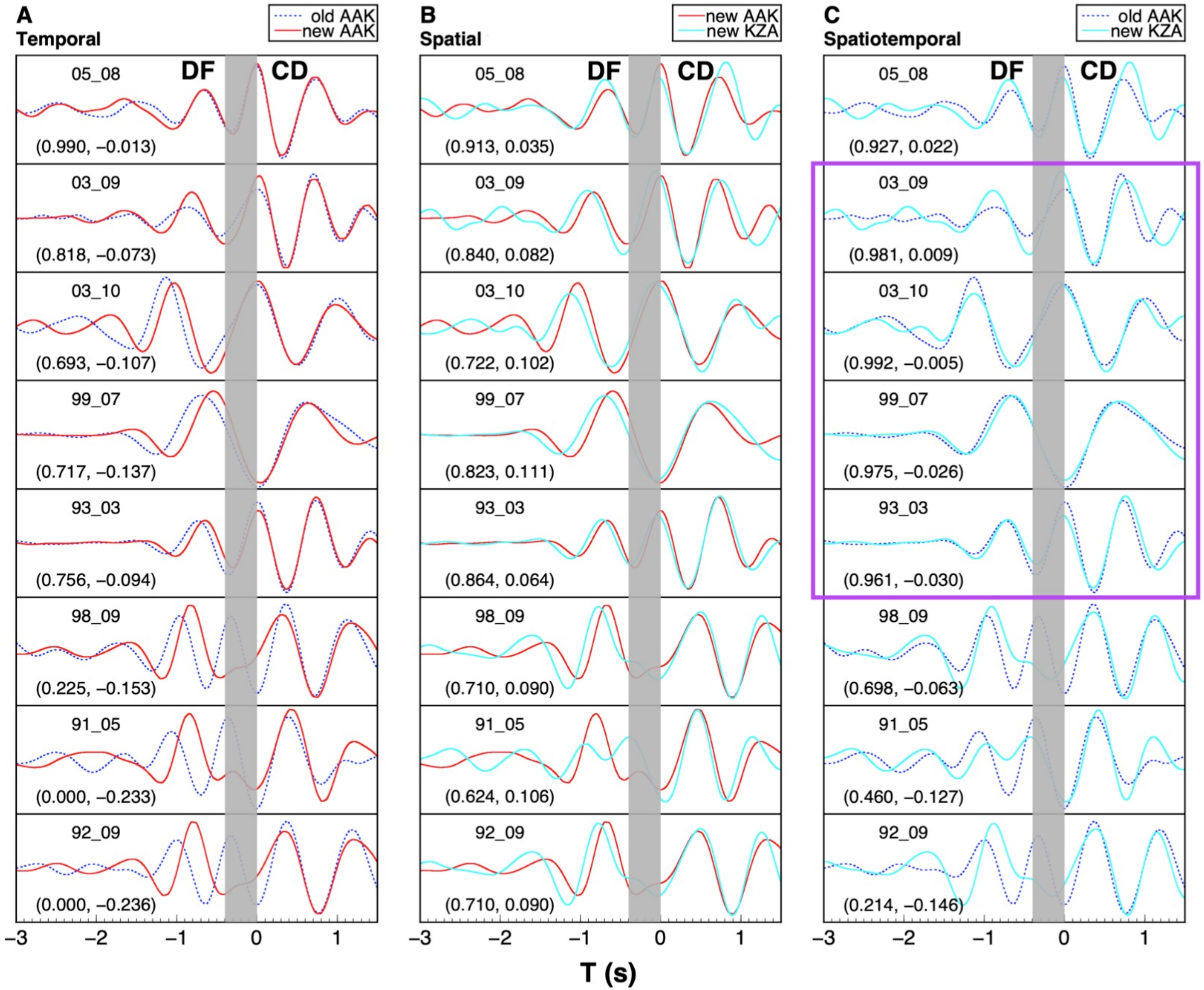


Figure 12. Similar to Fig. 11, but for more doublets. The pairs are in the order of increasing time lapse from top to bottom. The grey vertical bar marks the rough location separating the DF and CD arrivals. The waveforms in the purple box in C for the doublets of time lapses 6-10 years show relatively good matches, even though they are from different events and different stations.

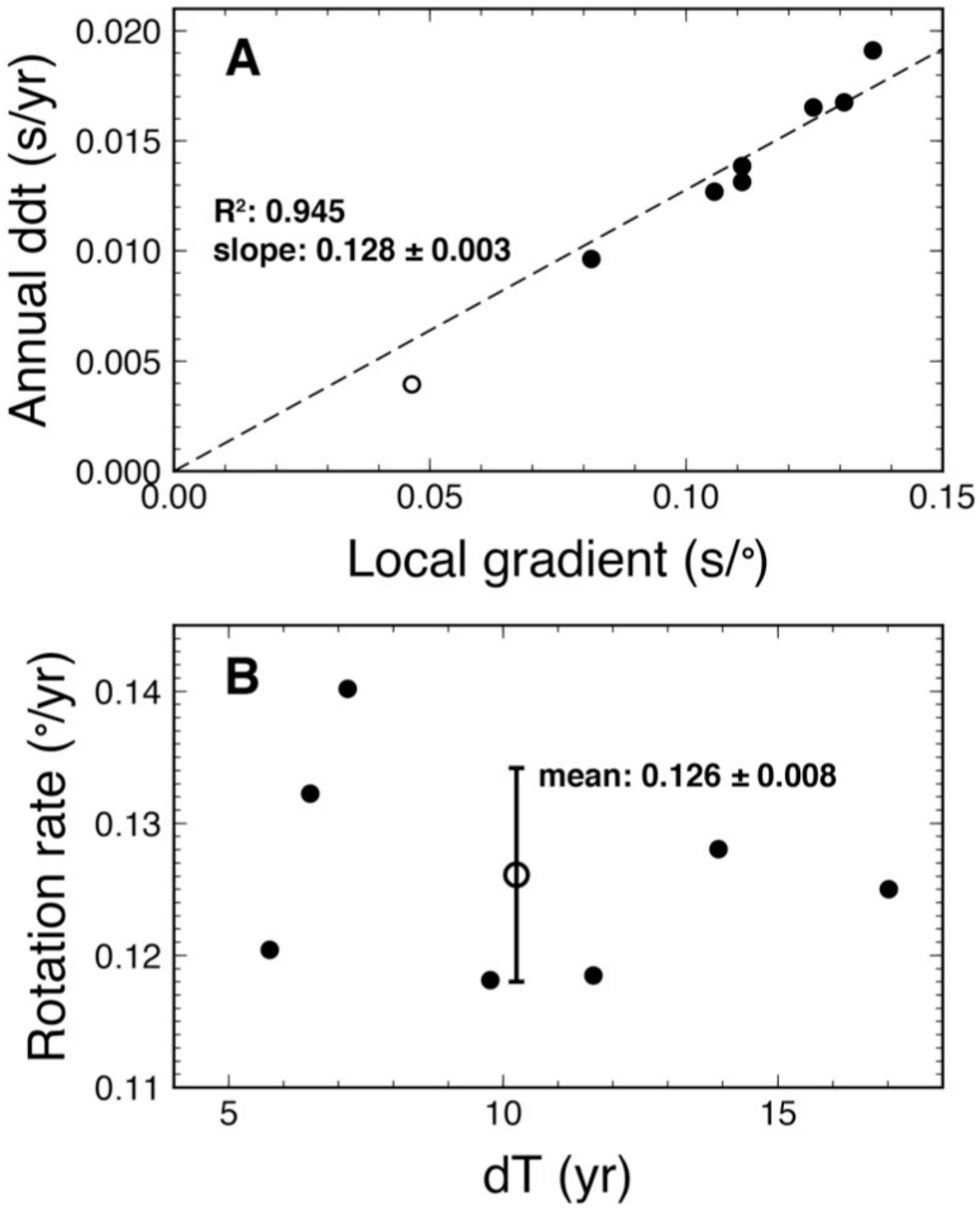


Figure 13. Estimations of the rotation rate. Two estimates (A, B) are made, yielding similar results (labeled, ~0.13° /year). The averaged annual ddt is defined as the temporal ddt (Fig. 12A) divided by the lapse of the corresponding doublet; and the local gradient is defined as the spatial ddt (Fig. 12B) divided by the longitudinal separation of the DF raypaths to the twin stations (Fig. 10). In A, the dashed line represents linear regression with zero intercept (excluding the data point from 05_08 with short lapse of 3.3 years, open circle). In B, a rotation rate is obtained for each doublet with lapse greater than 5 years by dividing the annual temporal change by the local spatial gradient. The open circle with error bar denotes the mean and standard deviation of all the measurements .

The rate is ~0.13° /year.

RECAP

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