

Bias in reported seismic arrival times deduced from the ISC Bulletin

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SUMMARY

The accurate timing of seismological data is crucial for most quantitative examinations in seismology. We present evidence that traveltimes from many stations contain systematic variations in timing which can be identified by checking the median of station delay times as a function of time. This function is expected to be constant but many deviations are found. Several hundred stations that report arrival times to the ISC have been examined. The median station delay times of almost 8 per cent of these stations show changes of more than 1 s and thus exceed the structural signal in the data. Temporal variations of 0.5–1 s are common. Changes in the distribution of observed earthquakes and other possible explanations of such variations have been tested and fail to explain most of the observations. Therefore, the bulk of the observed changes must be caused by flaws in the timing of the data or by biased picking of arrival times. For instance, at one station with a strong annual variation of noise level, the arrival times are on average picked several tenths of a second later during months with a high noise level.

Because of their systematic nature, these errors will not necessarily cancel out by using the large number of traveltimes in the ISC Bulletin and may therefore introduce a bias in many investigations. If the observed timing variations are due to the recording equipment at the stations, the errors will be present in the digital waveform data as well. Tomographic studies could potentially be affected, but in particular studies of temporal variations of Earth structure based on traveltime data, e.g. inner core rotation, need to be looked at with caution as results might be influenced by station effects. The exact nature of the bias is study-dependent and needs thorough investigation in each individual case.

Key words: ISC, *P* waves, *S* waves, seismic station, traveltime.

INTRODUCTION

The accurate timing of recordings is crucial in seismological research. Nowadays, seismometers and acquisition systems have reached unprecedented precision over a large band of frequencies and should help to pick traveltimes with high accuracy limited only by ambient noise. Unfortunately, the highest possible accuracy is not always reached in practice. Random and systematic errors reduce data quality and thereby pose limits to the results of seismological research.

The International Seismological Centre (ISC) Bulletin is a primary data set for many seismological studies; these have improved our understanding of the dynamics of the Earth, including plate tectonics, mantle convection and the geodynamo. Furthermore, its hypocentre information is used in a large number of seismicity studies (e.g. Adams 1985) and seismic risk analyses (e.g. Burton *et al.* 1984). The many different reported phases have led to numerous studies of Earth structure, such as regional and global tomography [for the

most recent studies, e.g. van der Hilst *et al.* (1997); Vasco & Johnson (1998); Bijwaard *et al.* (1999)], investigations of upper-mantle structure and discontinuities (e.g. Krishna & Kaila 1987; Kato & Hirahara 1991), studies of the core–mantle boundary and D' layer (e.g. Rodgers & Wahr 1993; Obayashi & Fukao 1997; Sylvander *et al.* 1997), measurements of inner core anisotropy (Morelli *et al.* 1986; Shearer *et al.* 1988; Su & Dziewonski 1995) and inner core rotation (Su *et al.* 1996). Davies *et al.* (1992), Robertson & Woodhouse (1996) and Su & Dziewonski (1997) used the Bulletin to determine the ratio of relative *S* to *P* heterogeneity, which can be used to constrain the mineral physics of the mantle. Further references may be found in the articles listed.

Recently, Engdahl *et al.* (1998) have taken ISC arrival times, with data from the USGS National Earthquake Information Center (NEIC) added for recent years where the ISC Bulletins have not yet been published, and relocated all events that are teleseismically well constrained. The use of a more accurate reference model and more phases, especially depth phases,

yielded a subset of improved quality which will certainly be used as a new reference data set for many studies. Recent tomographic models have already used these data and it will certainly be a source for numerous studies in the future. We used this data set for our investigation for practical reasons. However, we would like to stress that most of the problems encountered are inherent in the original data and are not due to the reprocessing of Engdahl *et al.* (1998).

The quality of the data set is hard to assess since it is mainly determined by the accuracy of the millions of original arrival time picks which were independently performed at the stations or network central sites using a variety of seismometers and acquisition systems. Hypocentres for some areas can be checked against high-quality localizations of regional networks. Errors for individual arrival times can only be estimated by statistical tests as done for random errors by Gudmundsson *et al.* (1990) for the original ISC Bulletin. In studies based on traveltimes, quality is normally improved by forming summary rays in which random errors will partly be cancelled out. Unfortunately, this is not the case for systematic errors which therefore have a high potential to introduce a bias into investigations. Gudmundsson *et al.* (1990) have concluded that ‘systematic errors are perhaps the most serious limitation of the ISC data’. A station bias related to the gain of stations was suggested and discussed by Grand (1990).

In this paper systematic changes of delay times at several stations are presented and various causes discussed. Variations of station time are detected by examining the temporal evolution of static station residuals. Lateral variations of upper-mantle and crustal structure cause significant deviations of traveltimes from predictions of 1-D earth models. The near-receiver effect is given by the mean station residual. A static (Cleary & Hales 1966) plus one (Bolt & Nuttli 1966; Herrin & Taggart 1968; Lilwall & Douglas 1970) or two (Dziewonski & Anderson 1983) azimuthal terms were fitted to all residuals of a particular station and subtracted from the traveltimes as a correction for aspherical Earth structure. The station residual is a measure of the near-station structure sampled by the distribution of ray paths. Therefore, it is expected to be the same for different time windows if their lengths are long enough so that the spatial distribution of earthquakes is similar within each window. For many seismological stations there are a large amount of reported arrival times which can be used to search for temporal variations of the station residual.

There are several possible reasons for a change of the station residual:

- (1) an error in the station timing system, e.g. a clock error;
- (2) a systematic change in the picking of phases, including effects caused by a change of the frequency band (e.g. a short-period seismometer that was replaced by a broad-band instrument) or by the use of different filters;
- (3) a movement of the seismometers if the station coordinates are not updated;
- (4) changes in the earthquake distribution observed at a station.

Only the last reason implies that the change is not caused by a systematic error. It is possible to identify such a case since it will also change some other properties, as outlined in the next section. Note that a clock error will also change the time information in digital waveform data, not just in picked arrival

times. However, for most stations it is impossible to distinguish between the first and second reasons from arrival times alone.

It is beyond the scope of this paper to discuss possible effects on studies that are based on the ISC Bulletin since these will depend very much on the particular methods which are used. However, the mean delay time of all stations does not show any significant variation in time and it can therefore safely be assumed that for the construction of 1-D earth models a bias for one station is compensated by the large number of other stations. The hypocentre determinations of larger earthquakes, which are recorded at many stations, will probably not suffer from any detrimental effects either. In contrast, investigations of regional differences that use the arrival times directly are much more sensitive to systematic changes at individual stations or networks and the bias will depend very much on the number of other stations in the area. In most cases the precise influence can only be estimated by extensive modelling.

Furthermore, many interesting aspects of current studies are close to the limit of what can be resolved in the data. For instance, tomographic models reveal small perturbations of only a few per cent from spherically symmetric earth models which give important insights into geodynamical processes. To improve these results even further it is certainly desirable to increase the accuracy of the data wherever possible.

IDENTIFICATION OF TIME VARIATIONS

In this study, delay times from the data set of Engdahl *et al.* (1998) are used. Delay times are the traveltimes (observed arrival times – origin times) minus the theoretical traveltimes in the 1-D reference model ak135 (Kennett *et al.* 1995). Additionally, corrections for ellipticity and station elevation taken from the same data set are subtracted. We verified that the bulk of the problems that are reported here are also present in the original ISC Bulletin.

About 350 stations have each reported more than 5000 *P*-wave arrival times during the 32 years covered by the data set. For these stations several independent estimates of the static station residual can be calculated and used to check the time information of individual stations. In order to do so we use a moving window over the period of operation for each station and calculate the median as a function of time of the window centre.

We illustrate the method first for delay times from station TUC (Tucson, Arizona). The top panel of Fig. 1 shows the mean deviation, which is defined as

$$\langle |\xi - \mu| \rangle,$$

where ξ are the individual measurements, μ is their median and $\langle \rangle$ denotes the expected value. In the middle panel the median μ can be seen surrounded by a 99 per cent confidence interval of the median (e.g. Rice 1995) displayed as a grey shade. This is based on the assumption that the samples are drawn from the same probability density function, which is doubtful for delay times since the spatial distribution of hypocentres is not equal in each time window. Therefore, the confidence level will be somewhat lower than 99 per cent. Nonetheless, such bounds are useful because they immediately show the relative accuracy of the median estimates for different times or stations.

The median was chosen as a primary indicator since the ℓ_1 -norm gives a more robust estimation of the centre for the distribution of delay times, which have long tails (Pulliam *et al.*

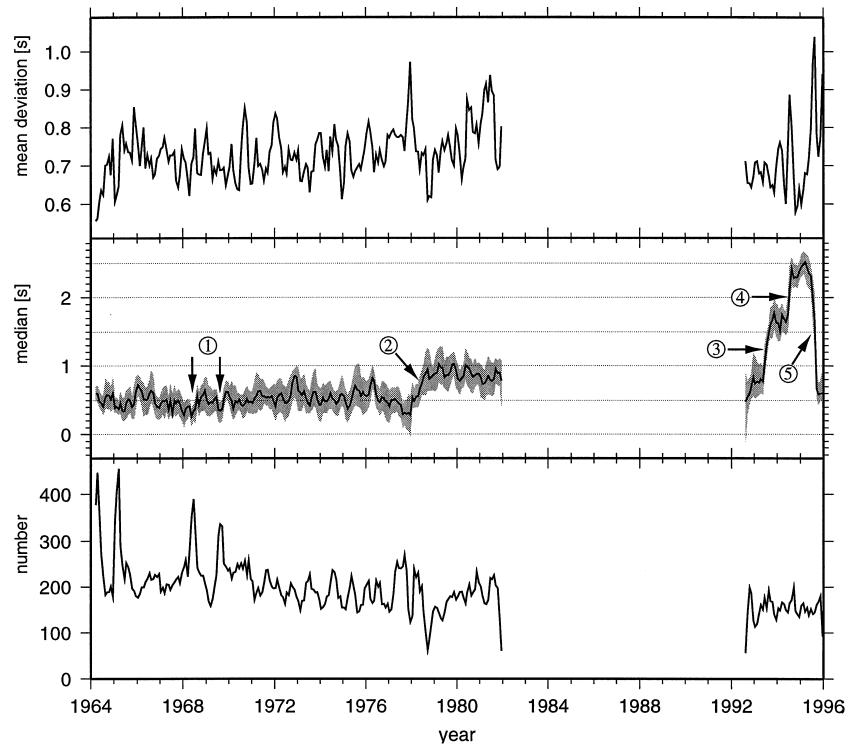


Figure 1. Moving window 3 months long applied to P delay times of station TUC. Upper panel shows the mean deviation, middle panel the median surrounded by an uncertainty of ± 3 median errors (defined in text) and lower panel the number of delay times falling in each window.

1993). In principle, the estimators for the ℓ_2 -norm can be used too. To do so the median and mean variation have to be replaced by the mean and standard variation respectively. A confidence interval can be calculated from the standard error. The disadvantage of the ℓ_2 -norm estimators is their enhanced sensitivity to outliers in the data; as a result they show more scatter. We have checked these indicators as well but do not show them in the figures since they do not contain any additional information.

The lower panel of Fig. 1 shows the number of delay times that fall in the window. Since this station reports many arrival times, a relatively short window length of 3 months is chosen for Fig. 1. The window is shifted in intervals of 1 month. In the following, several features labelled by circled numbers will be discussed.

Label ① marks two dips of the median which extend over the same length as the moving window. They can only be caused by anomalous residuals situated in the centre of the dips. The number of monthly events in the lower panel shows clear peaks at these locations and points to the explanation, which is the occurrence of two swarms of aftershocks from regions with early arrivals.

A step of the median from values of around 0.5 s to values of 0.8 s is labelled ②; this step is not large but is nonetheless clearly visible. From January 1982 until September 1992 the station did not report any arrival times to the ISC. After this gap the median undergoes dramatic changes in June 1993 ③, June/July 1994 ④ and August 1995 ⑤. The mean deviation (top panel) undergoes only relatively small fluctuations around a constant value and therefore does not indicate changes in the distribution of observed earthquakes. Larger jumps of the median are often accompanied by higher values of the mean deviation, as can be seen for the last two jumps (④ and ⑤).

However, the absence of large variations of the mean deviation and of the number of arrival times in Fig. 1 alone does not prove that the jumps of the median (②, ③, ④ and ⑤) are not caused by changes in the spatial distribution of observed earthquakes as is the case for ①. An important verification to rule out this possibility is to check whether a particular behaviour of the median can also be observed for delay times from sources in several different regions of the Earth. This is demonstrated for station TUC in Fig. 2. Because there are far fewer residuals for the individual regions, the moving window procedure will give larger fluctuations for the median. In order to compensate for this, the window length is increased to 12 months and the medians of the individual regions are smoothed over three points. As expected, each of the negative excursions ① occurs only in one of the regional curves, and this validates the idea that they originate from aftershock swarms. Further examination reveals that one happened at the Cocos–Nazca plate boundary and the other east of Hokkaido. On the other hand, jump ② is visible for all regions, as is the minimum just before it. Owing to the larger window length, the plateaux separating jumps ③, ④ and ⑤ cannot be seen any more, but the positive excursion is characteristic of all curves.

A different person started reading the phases for TUC in the Spring of 1976. In 1978 the console and recorder were moved to the University of Arizona and the sensors were connected to them by a phoneline. The latter period corresponds well to jump ② in the median delay time, which could be explained by delays in the telemetric system. Excursions ③ and ⑤ were due to the malfunctioning of an Omega clock which was not resolved until 1996 when a GPS system was installed. Thus, the data reported for the period 1992–1995 should not be used. Knowing these changes at the station allows one to shift parts of the data to probably the correct level for the years

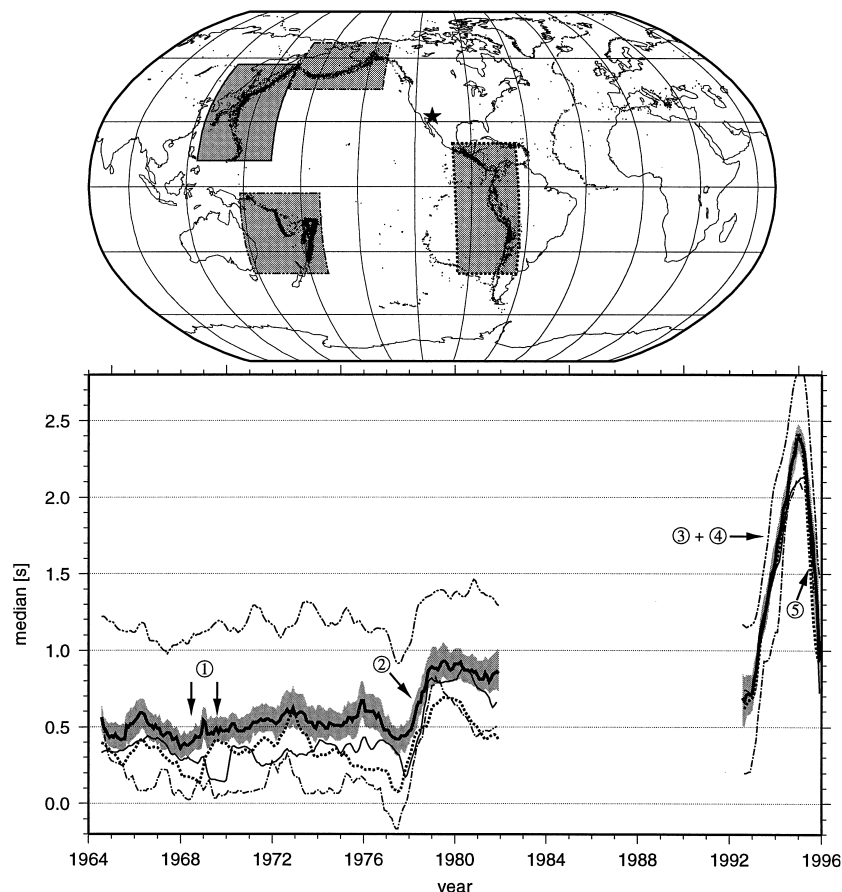


Figure 2. Solid line with grey shade shows median of moving window for station TUC as in Fig. 1 but this time for a window length of 12 months. The four additional lines are the medians of the same procedure for different source regions, which are displayed in the world map as grey shades. The line textures surrounding the boxes correspond to those of the different median curves shown in the lower plot. The station location is marked by a star in the world map. The window length was increased in order to have more residuals in each time window. In addition, medians for different regions are smoothed by averaging over three points.

before 1978. However, from the delay times alone there is no possibility of deciding whether the correct median for station TUC is around 0.5 s (as for the period 1964–1977), 0.8 s (as for the period 1979–1981) or whether it has yet another value.

The confidence band for many stations can be narrowed by shifting the delay times for different regions to a common level, in other words, by removing the azimuthal dependence of the station median. Additionally, this will slightly reduce the small random fluctuations. Fig. 2 shows, for instance, that at station TUC all waves arriving from the southwest are delayed by about 0.8 s relative to other source regions. Subtracting this value from the delayed arrivals will lower the mean deviation and the width of the confidence band.

It should be noted that such a small step as that visible in 1978 ② could only be detected because the station reports many phases. The period before 1978 for that station contains only very small fluctuations of the median compared to most other stations.

RESULTS

In this section more examples are presented. Fig. 3 shows five stations where temporal changes are found. Only the median of all *P*-wave delay times is shown, but for all stations that are

discussed in this paper delay times from different regions and the other parameters described in the last section have been checked to ensure that the variations are not caused by changes in the earthquake distribution.

Station FCC (Fort Churchill, Manitoba) in Fig. 3(a) is one of the most extreme cases. Between 1967 and 1984 the median shows very little variability around -0.4 s. After several years without any reported delay times the median is 1.5 s higher in 1992 for a few months (March until July, ①) before it further increases ② to 2.6 s where it stays for about 1 year (July 1992–September 1993). This is a total change of 3 s. After another break the median returns to its original value in 1995. A shorter time window reveals that the median has already decreased in October 1993, which cannot be seen with the 6 month window used in Fig. 3. During the years 1990–1994 the station had a short-period *z*-component seismometer and the signal was transmitted via a V-SAT satellite to Ottawa, where the time tagging was performed (B. Shannon, personal communication, 1997). This period coincides with the anomalous median, which can therefore be explained by an incorrect estimation of the transmission delay.

Fig. 3(b) reveals that for a 3 year period starting in 1985 (between ① and ②) the median of station LSA (Lhasa, China) is about 1 s lower than in other years. This is also evident in the

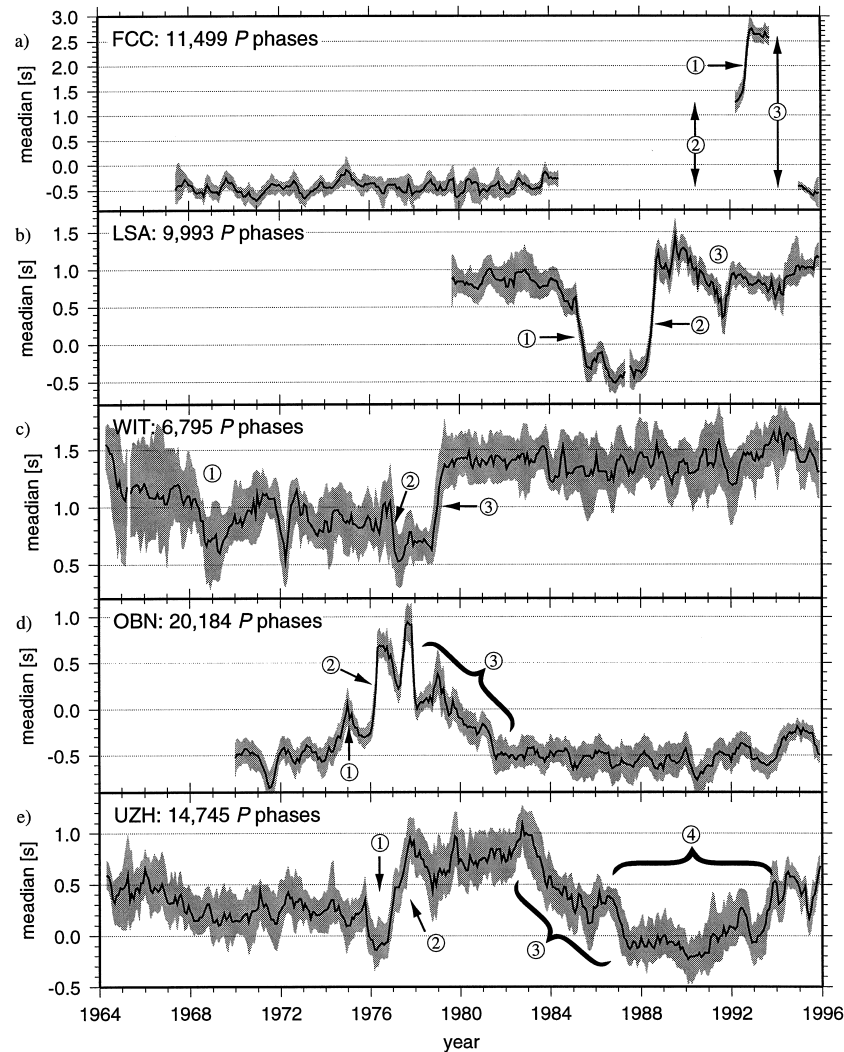


Figure 3. Examples of varying medians for stations FCC (Fort Churchill, Manitoba), LSA (Lhasa, China), WIT (Witteveen, the Netherlands), OBN (Obninsk, Russia) and UZH (Uzhgorod, Ukraine). The station code and the number of reported *P*-wave delay times appears on the upper left corner of each panel. Window length is 6 months.

residuals of several different regions, in contrast to the smaller variations in 1989 and later ③. Thus for the later variations it is not possible to decide whether or not they were caused by changes in the spatial distribution of the earthquakes that were picked.

Station WIT (Witteveen, the Netherlands) in Fig. 3(c) reported fewer arrival times to the ISC, which has led to a much greater uncertainty. Despite some variations in the beginning ①, two time intervals can be seen separated by a jump of the median of 0.5 s at the end of 1978/beginning of 1979 ③. At this time the seismometer and recording system were renewed (Grenet instrument with photographic paper to a Willmore MK-II with paper recording; R. Sleeman, personal communication, 1997). 2 years before that there is a very small drop ②. Again, ② and ③ are seen for residuals from different regions.

Variations in the examples shown can be identified easily as sudden changes at certain dates. Unfortunately, for most stations this is not the case. Variations are very often too small to be seen with the number of residuals available, or several

changes are so close to one other that they cannot be separated. Two more typical examples in this respect are stations OBN (Obninsk, Russia) and UZH (Uzhgorod, Ukraine), which are displayed in Figs 3(d) and (e) respectively. Nonetheless, a variation of the median can clearly be seen for all residuals and different regions. However, the localization of individual changes becomes more difficult. Changes in 1974 ① and 1976 ② for OBN are visible for individual regions as well; however, for the decrease after 1976 ③ it is not possible to decide whether it is a drift over a period of several years or whether it is caused by several smaller steps. Looking at individual regions only confirms a general decrease, but there are too few residuals to draw further conclusions.

Similar difficulties arise in the interpretation of station UZH. A relatively high median for the period 1977 ② to 1982 ③ and a small low for 1988–1991 ④ are evident. However, the trough in 1976 ① is seen by delay times from a few regions only and it is not known whether or not the decrease between these anomalous periods ③ is caused by only two jumps in 1983 and 1989.

Station location

A large change of the median can also be seen for station MAG (Fig. 4, Magadan, Eastern Siberia) in 1972. A shorter window than the 32 month window used for this figure shows that the jump happened in April 1972. However, Fig. 4 reveals a very different behaviour of medians for delay times from different regions, thus there is not a variation of the time at the station. Using the traveltimes and earthquake locations after 1973, the coordinates of the station were calculated. This revealed that the station has been moved to another location approximately 50 km to the north, which cannot be found in the coordinates provided by the ISC. This replacement is in agreement with the fact that in April 1972 the station did not report any phases.

The new location is very close to station MGD (Magadan 1), which started reporting phases in March 1973. For 515 events both stations report *P*-wave arrivals. For 403 events the arrival times are exactly the same and for only two earthquakes do they differ by 1 s or more. This shows that the seismometers are located very close to each other, probably even at the same site, or that the seismograms are picked twice. The fact that most arrival times match exactly is not very surprising considering the fact that most arrival times are only picked to a reading precision of 1 s.

Station networks

Not all stations are operated separately—some are combined in arrays or networks. For instance, the Swiss Seismological Survey operates a network of 27 stations. For most of these sites arrival times have been reported to the ISC. Fig. 5 shows the 7 stations for which the largest number of *P* phases have been reported. Data from stations ZUL and ZLA (both Zürich) have been merged because the seismometer has been moved only by about 150 m in 1986, which does not change the median, as can be seen in Fig. 5. All stations have a flat median after 1986, but between 1980 and 1986 a clear evolution towards later picks is visible. The most remarkable feature within this trend is a jump in 1982. Stations DIX (Grande Dixence) and ZUL show a negative trend until 1979. The similar behaviour is not surprising since the analogue seismometer signal of all 27 stations is telemetered to Zürich, where it is digitized, stored and analysed. Therefore, changes at the central site will influence the phase picks of all stations of the network in the same way. The jump of approximately 0.5 s in 1982 falls in the same year as a change of the analyst who picked the phases (H. R. Maurer, personal communication, 1997).

Another network where the data are analysed at one place is the LDG-CEA network in France. All stations belonging to this network show a slightly negative trend. In this case

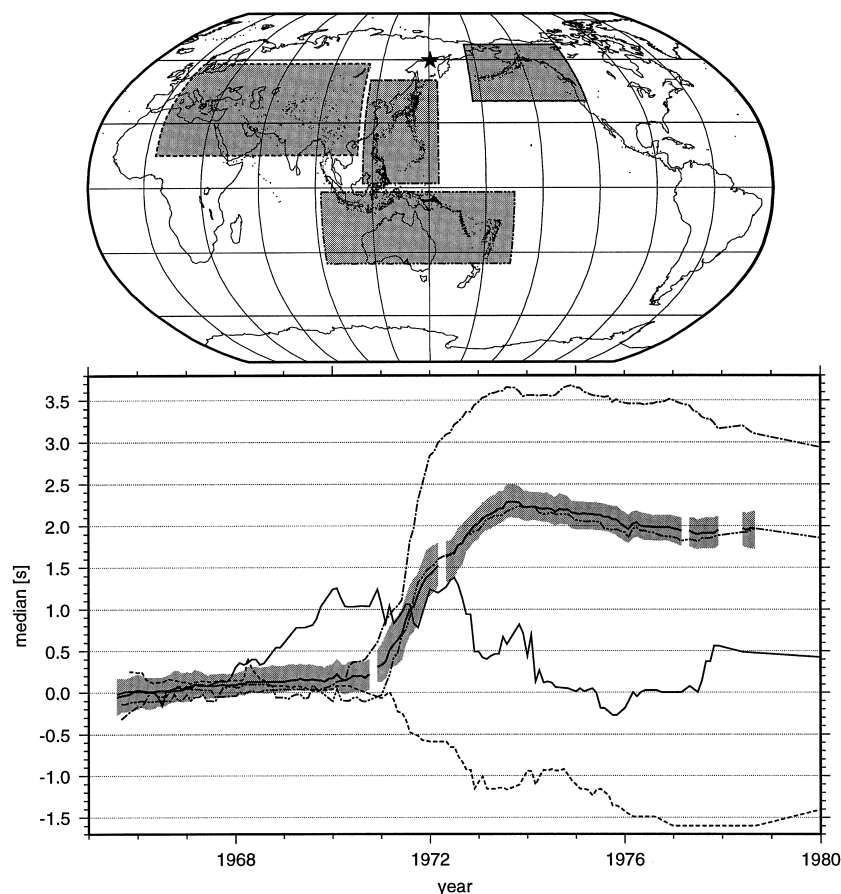


Figure 4. Same as Fig. 2, but for station MAG (Magadan, Russia) and a window length of 36 months. The median of all delay times shows a change of more than 1.5 s in 1972, but medians for individual regions show different jumps. This is probably caused by a movement of the seismograph of about 50 km to the north, which cannot be found in the coordinates of this station provided by the ISC.

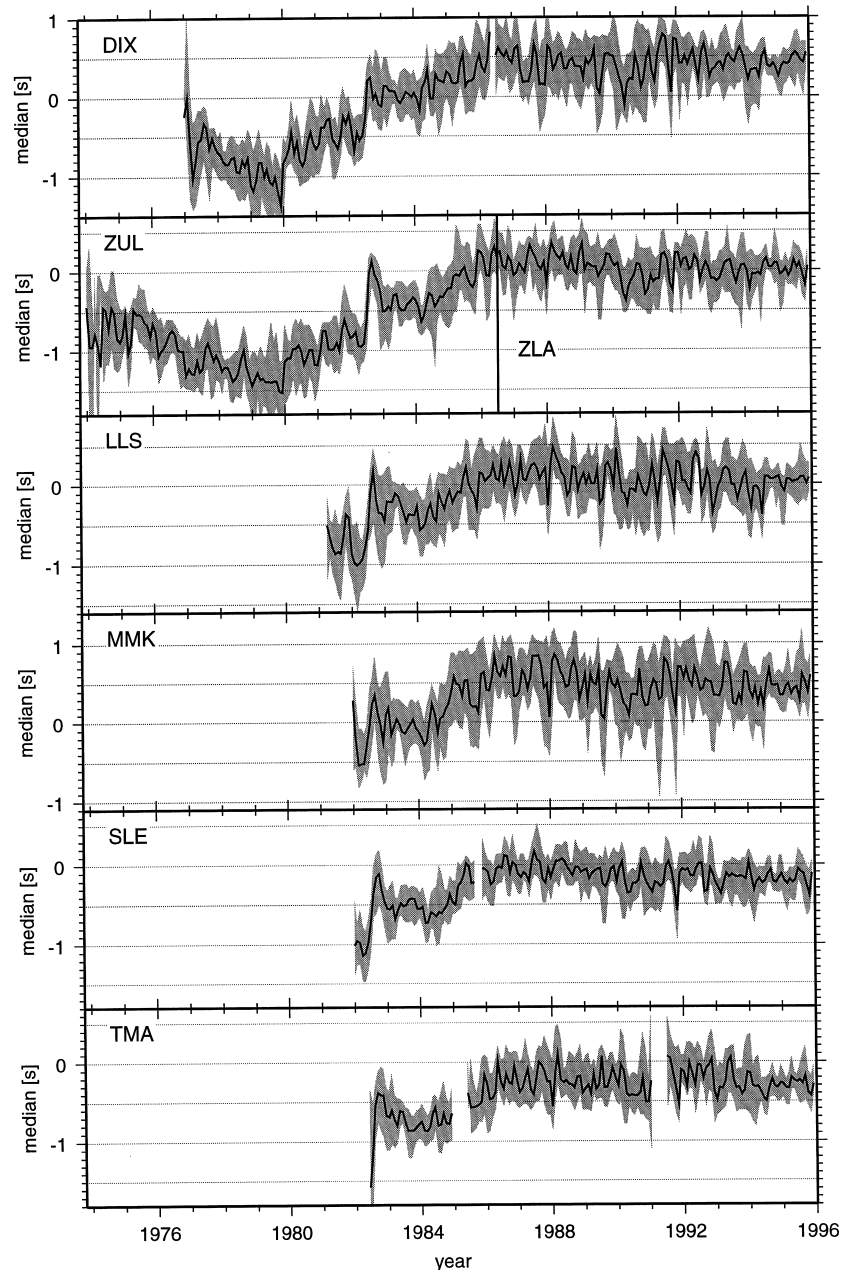


Figure 5. Medians for five stations of the network of the Swiss Seismological Service. Window length is 2 months. All stations show a jump in 1982 and an increase between 1984 and 1986. The stations are Grande Dixence (DIX), Zürich-Lageren (ZUL and ZLA), Linth-Limmern (LLS), Mattmark (MMK), Schleithem (SLE) and Tamaro (TMA). For explanation see text.

the variation is relatively small, and for an individual station it is close to the minimum value which can be recognized as a systematic change.

Changes in noise level

The Yellowknife Seismic Array (YKA, Northwest Territories) shows another interesting aspect (see Fig. 6). In addition to a different average median after a gap in 1989–1990 when the array was completely rebuilt [Station Book of the Federation of Digital Seismograph Networks (FDSN)], a distinct seasonal variation can be observed. The variation of reported delay times (lower panel), especially of small earthquakes, points to

a strong variation in the noise level, which agrees with the seasonal power spectral estimates in the FDSN Station Book. During months with a high noise level only about half as many phases are picked as during the period December to May. This variation is also found for different regions of hypocentres and different ranges of magnitudes. Therefore, it cannot be caused by the absence of reported small earthquakes during the second half of the year. The variation of the median is even stronger for large earthquakes, as can be seen in Fig. 7. This figure reveals two periods. Depending on the magnitude, the median is 0.25–0.7 s higher during July to October compared to December to May. This suggests that during periods with a higher noise level the first onset is difficult to recognize and

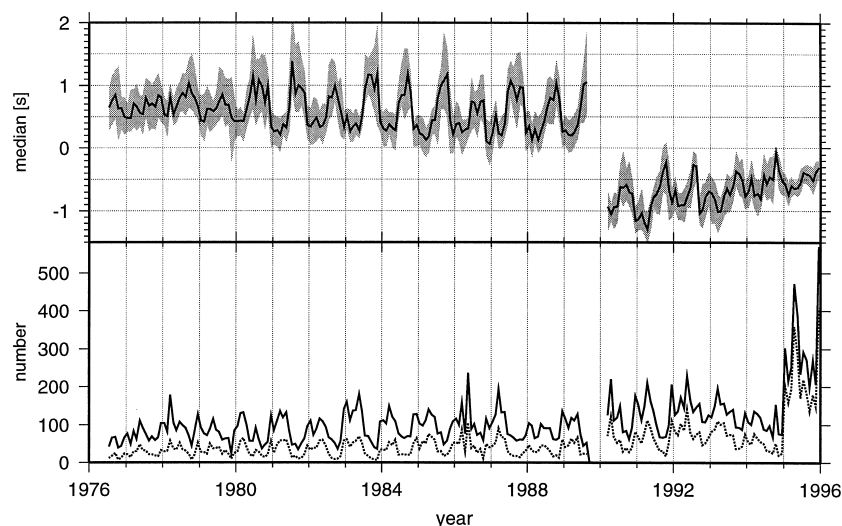


Figure 6. Result of the moving window technique for YKA (Yellowknife Seismic Array, Northwest Territories). The median (± 3 median errors) is displayed in the top panel. The total number of delay times (solid line) and that from earthquakes with magnitude lower than or equal to 4.8 (dotted line) is shown in the lower panel. Window length is 2 months.

therefore phases are picked several tenths of a second late on average. The magnitude dependence might be surprising but is probably a result of the relatively simple waveforms of small events and their generally more impulsive character. Thus, if small events are detected the resulting picks are more accurate compared to larger events with more complex waveforms and therefore the probability is higher that the onset is not seen correctly in the presence of noise and the arrival time is picked too late.

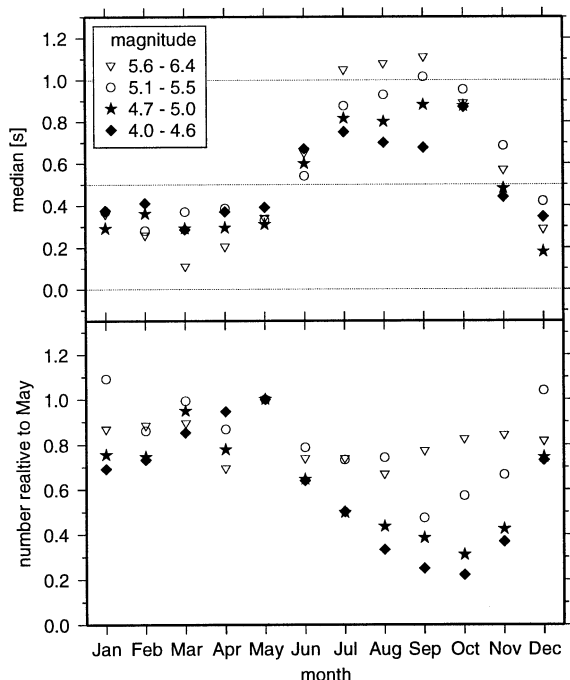


Figure 7. Median (upper panel) and number of delay times (lower panel) as a function of month for YKA. Symbols denote different magnitude ranges as defined in the box. For each month, data of the period 1979–1988 are used.

'Fake' arrival times

In the 1990s the United States National Seismograph Network (USNSN) started to generate 'fake' *P*-wave arrivals to include surface-wave magnitudes into the PDE system. This procedure was routinely applied to all USNSN stations with long-period channels whenever there was no *P*-wave trigger but surface-wave magnitude information (B. Presgrave, personal communication, 1998). In order to filter out these unreal data points they were always listed as *P* waves with arrival times given integer multiples of 10 s, resulting in positive residuals between 5 and 15 s. No onset quality or first-motion direction was assigned to them. The large positive residuals were chosen to prevent their use for other purposes. However, these arrivals were passed on to the ISC and can be found in their printed bulletins. Depending on the origin time of the ISC relocation a few might even have somewhat smaller residuals. Although the number of 'fake' arrival times (several thousand) is small compared to the total number of *P* arrivals, for some stations they can be the majority of arrival times, e.g. station HON (Honolulu, Hawaii) for 1991 and later. Some of the 'fake' arrival times will match closely the predicted arrival times of later phases, such as depth phases (*pP* and *sP*) or *PcP*. Consequently, they might be converted to these phases whenever a phase reidentification is carried out. Several hundred of these faked phases can indeed be found as later phases (primarily depth phases) in the data set of Engdahl *et al.* (1998) with small (positive or negative) delay times.

DISCUSSION

Since the examples have been chosen to be illustrative, most of them show above average variations of the station residual. It is desirable to estimate the extent of these errors in the complete data set. This is, however, not an easy task since each station shows a different pattern. Especially if stations which report not more than a few thousand residuals are examined and variations are not larger than 0.5 s, it becomes difficult to decide whether variations are caused by errors or by unequal

earthquake distributions. However, we try to give such an estimate. For the 299 stations that report at least 5000 teleseismic arrival times the maximum variation of the median for a moving window is shown in Fig. 8. We restricted this analysis to teleseismic events, that is, epicentral distances larger than 30° , to exclude the much larger delay times of regional events, although the median is not very sensitive to them. The window length was not chosen to be a fixed period of time as in the examples shown but as the period in which 1000 residuals fall. This means that for a station that reports few P phases the window length can be several years whereas for others the window length is only several months, e.g. station TUC. The length of 1000 residuals was chosen because it recovers the maximum variations of the median in the examples shown quite well, e.g. 1.74 s for TUC, 2.64 s for FCC and 1.57 s for LSA, and still smooths random fluctuations of the median. Note that the chosen length is larger and thus the smoothing stronger than those used in any of the examples presented. The minimum number of residuals ensures that for each station at least five completely independent values for the median are obtained.

The 299 stations examined for Fig. 8 have contributed 64.5 per cent of the teleseismic P phases in the database, although they represent only 7.0 per cent of the stations. Not all variations are caused by systematic errors. Different distributions of earthquakes and random errors also cause some small fluctuations. A good station without systematic errors has variations of only a few tenths of a second. For example, station TUC (Figs 1 and 2) has a maximal variation of the median of 0.28 s for a window length of 1000 delay times for the period 1964–1976, where it can be considered as a good station. Thus, variations of less than approximately 0.5 s are not necessarily caused by errors. On the other hand, systematic errors of only a few tenths of a second or which are short in time are not detected. Variations larger than 0.5 s are

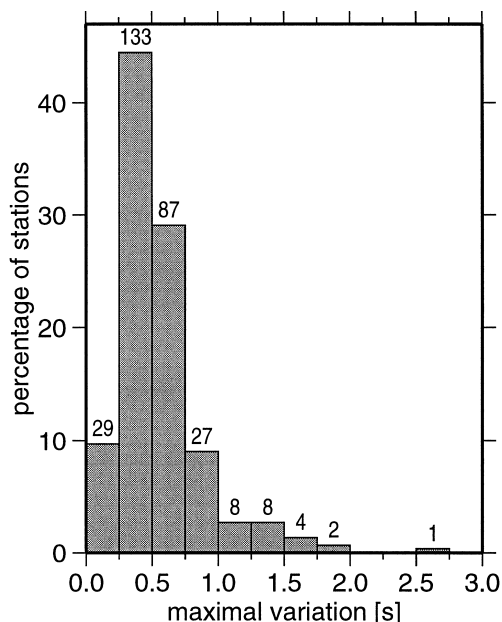


Figure 8. Histogram displaying the percentage of stations that have a maximum variation of the median denoted by the abscissa. The number of stations appears at the top of each column.

very unlikely to be explained by the earthquake distribution alone and at least part of the deviations stems from errors. 137 stations (45.8 per cent) show such large variations. For 23 stations (7.7 per cent) there are changes of 1 s or more. These numbers should be compared to the mean deviation of teleseismic P delay times, which is 0.9 s if the distribution is cut at ± 3.5 s as is usually done in tomography for teleseismic waves.

What are the possible causes for such systematic variations? Earthquake distribution cannot be responsible for at least the larger variations since they can be identified from travel-time data by looking at different areas, magnitudes, depths, etc. Since the collection and processing of the arrival times by the ISC, as well as by the National Earthquake Information Center (NEIC) and the relocations of Engdahl *et al.* (1998) are carried out for all events and stations in the same way this cannot explain changes for individual stations either. The obvious possibility is that the observed changes are caused by instrumental or phase picking errors. In the case of instrumental problems, all work based on the original seismograms would also be influenced except when using relative times, e.g. differential traveltimes between phases.

The simplest error would be an incorrect time of the station clock. Delays in the acquisition system that are not corrected would have the same effect. Such errors are most likely to occur when equipment is replaced. Indeed, many of the jumps in the examples shown coincide with gaps, which suggests that a change of equipment has taken place.

On many seismograms the precise onset is not obvious and different people (or automatic pickers) will not always pick it at the same time. For the Swiss stations, for instance, a change of analyst probably explains as much as 0.5 s difference on average of all picks. Digital stations can be very helpful with their possibilities of filtering the data and enlarging the displayed seismogram. On the other hand, they might also be a source of errors if instrument corrections or filters are applied incorrectly, for example the use of zero-phase instead of causal filters. The transfer function of the instrument can also have a large influence and distort the onset.

Station YKA demonstrates that the noise level can be crucial for correct picking. A dependence of arrival times on the gain, which is normally adjusted to the noise level, for the ISC Bulletin has already been suggested by Grand (1990). Douglas *et al.* (1997) demonstrated for some examples how the correct onset cannot be seen until the magnification is large enough so that the noise before the phase is clearly visible. If the onset is weak it will probably be missed at stations with a high noise level.

Systematic errors are present in all phases, not only P . As an example, Fig. 9 shows the P phase together with the core phases PKP_{AB} , PKP_{DF} and $PKiKP$ for station BNG. Although the number of core phases is relatively low compared to P and the uncertainties are therefore much larger, a jump in 1972, smeared out over the window length, is present in all phases.

Errors of station time are thought to be avoided by using differential traveltimes of two phases from the same event recorded at the same station, but if errors are caused by the picking procedure they may still be present. Picking of onsets may depend on the noise level or the frequency content of phases and are likely to be different for first-arriving and later phases. Examples where the changes of different phases are dissimilar can also be found, especially in comparisons of P and S phases. This is demonstrated in Fig. 10 for delay times

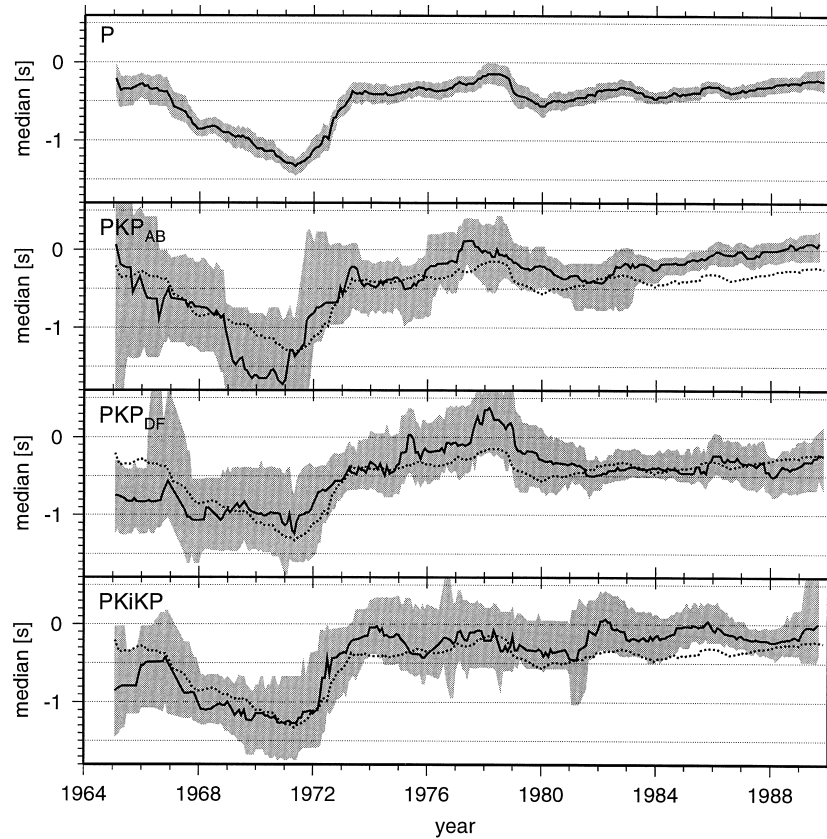


Figure 9. Similar behaviour of the median for delay times of four different phases observed at station BNG (Bangui, Central African Republic). Phase names appear in the upper left corner of each panel. Window length is 24 months. The median of the *P* phase (uppermost panel) is repeated in the other panels as dotted lines for ease of comparison.

from station HYB (Hyderabad, India). Whereas no significant change in *P*-wave delay times occurs, the median of *S* phases does show large variations of more than 1 s. Generally, we find that variations of *S* phases are much larger than those for *P*. This can be understood by the fact that due to scattered waves the noise level present at the *S*-wave arrivals is higher, which results in a poorer quality of the picks. Furthermore, there is a difference in the frequency content, and whereas *P* phases are picked from the short-period *z*-component, *S* waves may also be picked from horizontal components or long-period channels. Different behaviour may be present in other phases as well, thus even differential traveltimes can be influenced by changes in picking.

From our findings it is clear that searching for time-dependent variations of velocity structure inside the Earth

with ISC traveltimes needs to be carried out very carefully. Whenever temporal variations are interpreted as changes inside the Earth, for example inner core rotations determined by ISC data (Su *et al.* 1996), many different phases should be checked in order to rule out possible station biases. Unfortunately, only very few stations report enough residuals of different phases that could be used to separate hardware errors, picking errors and changes inside the Earth. ‘Fake’ arrival times may have an undesired influence if a cut-off value is not chosen smaller than 5 s. If residuals of 5 s and more are included, these arrivals will bias all USNSN stations to late arrival times for the 1990s. This will be a systematic bias concerning time and region. Tomographic modelling is also potentially affected, but to what extent needs to be investigated by extensive numerical simulations.

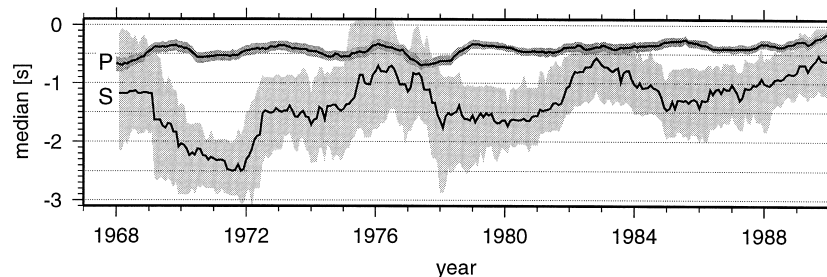


Figure 10. Different behaviour of *P*- and *S*-wave delay times recorded at HYB (Hyderabad, India). The much smaller number and generally poorer quality yield the broader confidence interval for *S* waves. Window length is 18 months.

The fact that there are stations with periods of a constant median separated by identifiable steps, e.g. TUC, FCC, LSA or WIT, raises the question whether independent station corrections for each period would correct the data. Since the times of changes can only be estimated with some uncertainty, some residuals around the steps would have to be deleted in order to be certain that no incorrect correction is applied to them. Another problem is that if the changes are caused by the picking procedure, the variations might be dependent on magnitude or other parameters, and applying constant time-shifts would be incorrect.

For most other stations it is much more difficult and in many cases even impossible to construct time-dependent station corrections that remove offsets caused by errors while leaving the structural signal in the data. If the time variation is limited in time, removing part of the data would be another possibility for obtaining a smaller data set, hopefully with reduced errors. This could be done for station OBN, for instance. However, for the majority of stations correcting the data is not an option since they report too few arrival times in order to identify individual changes. In all cases, whether the data is corrected or not, the average station residual has lost the meaning of being a measure of near-receiver structure. Rather, it is for many stations a sum of this and systematic time errors, with both parts being of a comparable size.

CONCLUSIONS

Delay times of the database of Engdahl *et al.* (1998) have been tested for systematic variations in time. For 46 per cent of the stations examined changes of the median delay time of more than 0.5 s have been found. Several examples have been presented and analysed to rule out causes that do not originate at the stations. Consequently, our conclusion concerning these stations is that either the station timing system or the phase picking procedure introduced systematic errors for certain periods in time.

The causes are manifold and include picking errors as well as hardware changes. Different behaviour of the median for different phases points to systematic picking errors. Unfortunately, this can also bias differential traveltimes of different phases from the same event as shown in Fig. 10 for *P* and *S* waves observed at station HYB. Since some of the variations are very large, e.g. at station LSA (Fig. 3), it seems unlikely that they could be explained by picking errors alone but rather are caused by the instrumentation. In this case the time errors will not only be inherent in reported arrival times but also in the waveform recordings. However, it is impossible to find out the exact cause from the reported arrival times without any additional information.

Although each station affects only a small number of phases compared to the total number of data in the ISC Bulletin, the errors potentially influence quantitative seismological results because the errors discussed are not random but systematic for individual stations or even networks, e.g. the Swiss regional network. Studies of temporal variations of Earth structure in particular are prone to the reported biases due to the systematic changes in time of the errors. Tomographic studies will probably also suffer from these effects, although the exact extent can only be detected with intensive modelling. We anticipate that they are most affected in regions with sparse station coverage where model parameters are resolved by few

summary rays and systematic errors cannot be compensated by rays to other stations. In general, the implications for individual studies will depend strongly on the methods applied.

Observational seismologists should be aware of this and test results for possible biases induced by time errors. We recommend that seismological stations implement more checks on the accuracy of timing in order to detect malfunctions and to reduce errors in the future.

Information on other stations can be found at <http://www.geo.uu.nl/~roehm/Station.Time>.

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