CEPSTRAL F-STATISIC PERFORMANCE AT REGIONAL DISTANCES

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ABSTRACT

We have developed a cepstral F-statistic method that attaches statistical significance to peaks in the cepstra of seismic data. These peaks often result from echoes such as depth phases and thus provide a means of identifying possible depth phase candidates. Detections from this method are stacked as a function of their *pP-P* and *sP-P* delay times predicted by IASPEI travel-time tables using a modified version of the network stacking method of Murphy *et al*. (1999). The method detects depth phases with signal-to-noise ratio (SNR) greater than 2, as long as the P wave SNR is greater than 5 to 8, providing a wide range of applicability. We have tested the method on limited datasets from the United States Geological Survey, the Prototype International Data Center, and the International Data Center, and have shown the method to be more reliable at automatically picking possible depth phases than current algorithms. We are now in the process of further testing the method using the extensive datasets at the Research and Development test bed at the Center for Monitoring Research.

We have successfully applied the method to events with epicentral distances greater than 12 degrees and focal depths greater than 15 km. Our focus during the past year has been to examine the technique at near-regional distances for small-to-moderate sized events of varying depths. To accomplish this task, we have acquired a high-quality ground-truth dataset compiled by Ratchkovski and Hansen (2001) using the Alaska Earthquakes Information Center (AEIC) network. We have chosen a subset of the 14,000 events they relocated with magnitudes ranging from 3.5 to 5.1 (M_L), and we are in the process of applying the method to the seismic data recorded for these events at regional distances (using arrays/stations ATTU, BCAR, BMAR, KDAK, ILAR, and IMAR). We are comparing our cepstral depth phase detections at regional distances with depth calculated from data recorded at teleseismic distances (PDAR, MNV, and YKA). For the preliminary analysis at regional stations, the peak created by the *sPn* arrival is the phase most often detected by our cepstral F-statistic method for sub-crustal events. Often, the geometry of the ray paths at regional distances results in *sP* being the only depth phase predicted and observed. We use this *sPn* peak to independently confirm the network-calculated depths for several events of the AEIC dataset. However, in some cases, the improper classification of this peak as *pPn* has resulted in more than doubling the true event depth, thus creating a screening faux pas. Our results thus far show that the method can be applied to regional data with success; however, additional tools may be needed to help determine the true identity of the depth phase (*pP* vs. *sP*).

KEY WORDS: seismic, depth phases, cepstrum, F-statistic, event-screening

OBJECTIVES

The depth of a seismic event is one of the most compelling characteristics seismologists have to determine if an event is man-made or not. Unfortunately, the depth is also notoriously difficult to determine accurately. Some of the methods used to determine focal depth include waveform modeling, beam forming and cepstral methods for detecting depth phases such as *pP* and *sP*. To improve depth estimation using cepstral methods we focused on three primary objectives: (1) formulating a method for determining the statistical significance of peaks in the cepstrum, (2) testing the method on synthetic data as well as earthquake data with well-determined hypocenters, and (3) evaluating the method as an operational analysis tool for determining event depths using varied datasets at both teleseismic and regional distances.

We have successfully completed most of each of the objectives, and we will briefly describe our research to develop and test a cepstral F-statistic. A few additional questions have surfaced during the past year, including:

1. Is there any way to reduce the false alarm rate in the cepstral F-statistic?
2. How are depths determined based upon cepstral F-statistic peaks at different arrays/stations?
3. Can the method be successfully applied to near-regional events?

In the following section, we will provide results of our attempts to answer these three important questions.

RESEARCH ACCOMPLISHED

We have formulated a cepstral F-statistic using a classical approach to detecting a signal in a set of stationary correlated time series (Shumway *et al*., 1998). The method is particularly suited for regional array analysis (Bonner *et al*., 2000); however, the method can also be applied to three-component data (Shumway *et al*., 2000). Tests on synthetic data show the method works best when the *P* wave arrival has a signal-to-noise ratio (SNR) greater than between 5 and 8 with the depth phase exhibiting a SNR greater than between 2 and 4. These requirements in SNR were validated using events from the Hindu Kush region of Afghanistan with well-determined depths calculated from data recorded on arrays at teleseismic distances.

To test the operational capabilities of this method as a tool for data center use, we analyzed 61 events located by the National Earthquake Information Center (NEIC) and/or the Prototype International Data Center (pIDC). Our method determined statistically significant depths for 41 of 61 events. Ten of the events had low SNR at the recording arrays, while another 10 were either too shallow for analysis or did not exhibit depth phases. The method determined depths between 12 and 90 km for 7 of the 17 events which the pIDC had fixed to 0 km. The scatter between the cepstral F-statistic depths, the NEIC depths and the pIDC depths decreases significantly as the magnitude increases. The F-statistic method works best for teleseismically recorded events with magnitude greater than 4.0; however, similar analysis using far-regional data (12 - 20 degree) has shown success as well. Overall, we believe the method would be most valuable if used as a tool by the analyst to help highlight possible depth phases for further review. During various reviews of our research, several important questions and concerns emerged, and some of these topics are discussed in this paper.

False Alarms in the Cepstral F-Statistic

One of the concerns that arose while developing the cepstral F-statistic method involved multiple peaks that resulted in potential false depth phase picks. Multiple peaks that exceed the 99% confidence level in the cepstral F-statistic will complicate the analysis for the peaks associated with the actual depth phases. Figure 1 shows the cepstral plots for a synthetic event with a depth of 46 km. The *pP-P* delay time should be at 13 seconds, and a large peak in the cepstral F-statistic does indeed correspond to this time. However, at 25.5 seconds, there is an additional smaller amplitude peak that rises slightly above the 99% confidence level. Based upon our detailed analysis, false alarms (i.e. peaks in the cepstral F-statistic not associated with depth phases) result from two different cases. The first is the arrival of post-*P* phases that have similar spectral characteristics to the *P* waves and thus the cepstra stack as if they were depth phases. We have found that changing the pre-processing filter parameters and/or the tapering window in the log spectrum (for the processing flow, the reader is referred to Bonner *et al*., 2000) at different frequencies may attenuate these peaks; however, in most cases these false alarms will always exist in the cepstral F-statistic and thus must be considered as potential depth phase candidates. In a later section, we will discuss a method of depth phase beam forming that can reduce the impact of these false alarms. Another case of false alarms occurs when the quantities that form the cepstral F-statistic, the beam cepstrum and the total cepstrum, exist in close proximity to each other through random processes. This explains the peak at 25.5 seconds in the F-statistic of Figure 1, where a small peak in the beam cepstrum is accompanied by a decreasing trend in the total cepstrum, resulting in a false alarm. Often, using a slightly different window of data or changing the filter or smoothing components will remove this false alarm, but instead, we search for peaks in all three cepstral quantities prior to classifying it as a cepstral F-statistic detection.

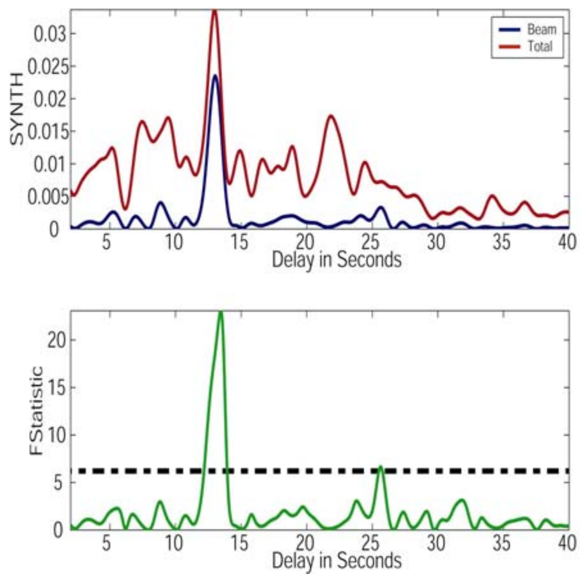

Figure 1. (Upper) Beam and total cepstra for synthetic array data for an earthquake at 46 km depth. The beam cepstrum is formed by summing the detrended and windowed log spectra. The total cepstrum is formed by stacking the individual cepstra. (Lower) The cepstral F-statistic is calculated using both the total and beam cepstra, and shows a large peak above the 99% confidence level (black dashed line) at 13 seconds and a smaller peak at 25.5 seconds.

Depth Determination from Cepstral F-Statistic Detections

During the earliest stages of this research, we were employing a crude and subjective method for determining depth of a seismic event based upon the cepstral F-statistic peaks. Our method was meant to complete the analysis on as many arrays as possible and to visually correlate the depths determined from the cepstral peaks among the different arrays. This may lead to one depth that is consistent at all arrays considered in the analysis, or there may be numerous plausible depths. It became clear that this method introduced the potential for human error into the analysis.

We tested the method of depth phase beam forming as first suggested by Israelsson (1994) and applied by Woodgold (1998). Murphy *et al.* (1999) has modified the method to place one-second boxcar windows centered on post-*P* detections generated by the automatic processing at the pIDC and then stack them as a function of *pP-P* or *sP-P* delay times predicted by IASPEI travel time tables. This method has shown remarkable success at highlighting depth phases for analyst review. An example of the application of this method for an event in Argentina (IDC Evid 592530) with an IDC reported depth of 107.6 ± 3.9 km is shown in the left panel of Figure 2. We have modified the method to stack cepstral F-statistic detections instead of post-P detections, and we have decreased the boxcar width from 1.0 second (Murphy *et al.*, 2000) to 0.6 seconds in order to decrease the width of the beam-formed peaks. In the right panel of Figure 2, we show the results of stacking the cepstral F-statistic detections for the same pIDC data used to create the left panel. Both plots show large peaks associated with a depth of 108 km; however, note that we find three additional detections among the IMS stations using our method. In this case, three additional stations do not change the results significantly, as this event was large enough (m_b=5) for obvious depth phases to be observed at multiple stations. We present examples in Figures 3 and 4 that show the same analysis on smaller events for which the detection of the depth phase is more difficult. In the example in Figure 3, a Hindu Kush event (pIDC Evid 20085674) depth was determined by network hypocenter determination at 140.8 ± 19.7 km with no depth phases incorporated in the solution. Stacking of the network post-P detections shows two detections that correspond to this depth; however, stacking of the cepstral detections show six peaks at this depth. A third event (Figure 4) from Oaxaca, Mexico (pIDC Evid 20785471) had a pIDC reported depth of 95.8 ± 54.7 km with no depth phases. Our analysis shows five detections that correspond to a depth of 17.2 ± 2.5 km. This depth is more plausible than the pIDC depth, because the epicenter of this event is near the trench of the Mexican subduction zone, where historical data suggest the events are at crustal depths. The results thus far are quite promising that the Murphy *et al.* (1999) method of depth phase beam forming will provide a robust, automated method of translating cepstral F-statistic peaks to a depth.

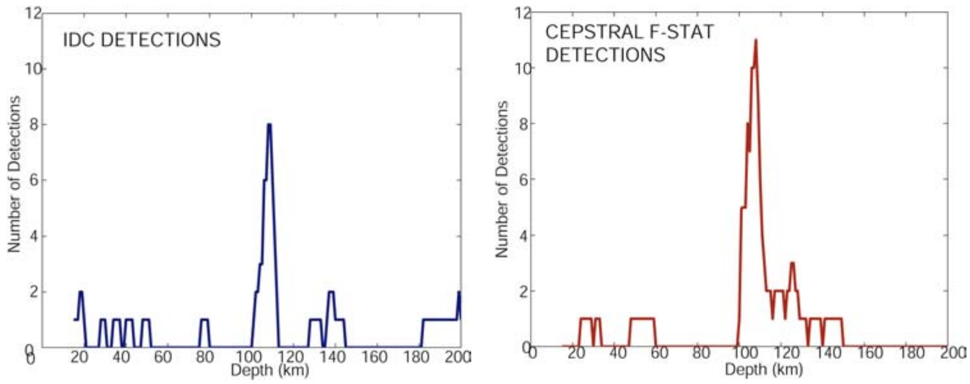

Figure 2. (Left) Network stacking of post-P detections at the IDC for an event in Argentina (IDC Evid 592530). (Right) Network stacking of cepstral F-statistic detections. Both plots show large peaks associated with a depth of 108 km; however, note that we find three additional detections among the IMS stations using our method. The IDC depth for this event is 107.6 ± 3.9 km.

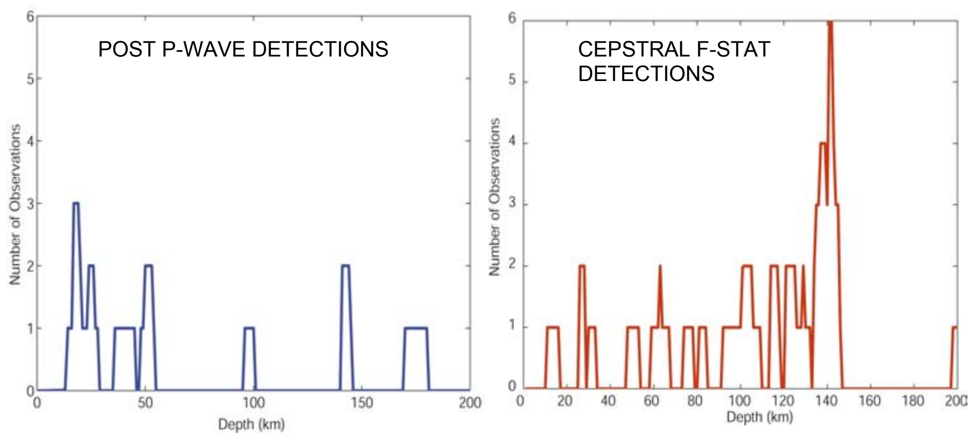

Figure 3. (Left) Network stacking of post-P detections at the pIDC for an event in Hindu Kush (pIDC Evid 20085674). (Right) Network stacking of cepstral F-statistic detections. The cepstral analyses show a six detection peak associated with a depth of 140.9 ± 5.5 km that agrees with the pIDC depth for this event of 140.8 ± 19.7 km with no depth phases reported.

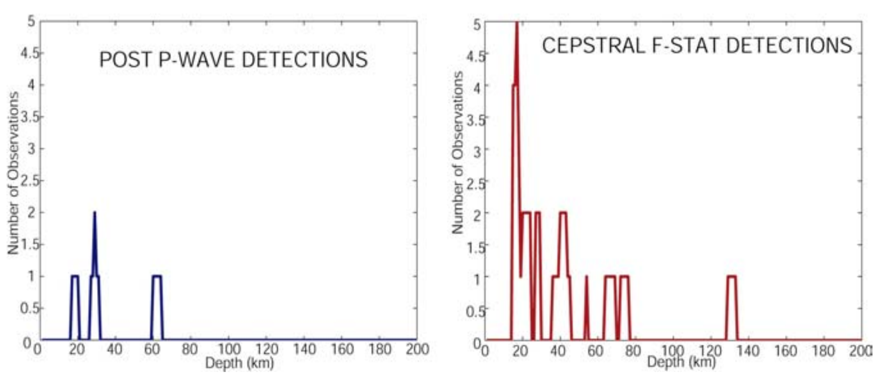

Figure 4. (Left) Network stacking of post-P detections at the pIDC for an event in Oaxaca, Mexico (pIDC Evid 20785471). (Right) Network stacking of cepstral F-statistic detections. The cepstral analyses show a five detection peak associated with a depth of 17.2 ± 2.5 km that disagrees with the pIDC depth for this event of 95.8 ± 54.7 km.

Cepstral F-Statistic Analyses on Regional Data

Near-regional cepstral analysis is complicated by a number of factors, including emergent and low SNR *Pn* arrivals and complicated *Pn* and *Pg* coda. If one is relying upon the cepstral analysis at regional stations for a depth estimate, it is probably because the event has an $m_b < 4.0$, which translates to smaller amplitudes and SNR in some cases. Another complexity is related to the nature of the ray paths for depth phases at near-regional distances. Figure 5 shows the initial distance from an event to a station in which a depth phase (either *pPn*, *sPn*, *pP*, or *sP*) is theoretically predicted to occur as a function of the event depth in the IASPEI91 model (Kennett and Engdahl, 1991). For near-regional distances (< 10°) and crustal events (< 35 km) , IASPEI91 predicts *pPn* and *sPn* may be observed at distances greater than 1°. However, for events that occur deeper than the crust-mantle interface, *sPn* will be the only observable depth phase. For many of the events thus far analyzed at regional distances, *sPn* has been the only depth phase detected by the cepstral analysis. We originally classified these peaks as *pPn* resulting in the events being placed deeper than they actually occurred. The depth phases *pP* and *sP* are predicted at 14° which correlates with our previous studies (Bonner *et al*., 2000) that demonstrated the cepstral F-statistic method can be applied successfully at distances greater than 12°. The question remains as to how the method will work in an operational setting for epicentral distances less than 12 degrees where *pPn* and *sPn* are the predicted depth phases.

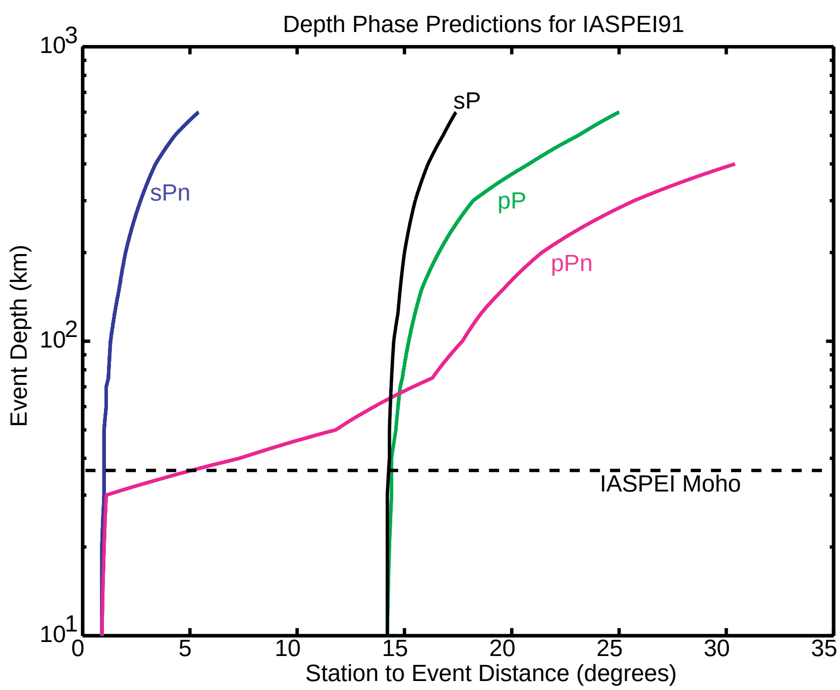

Figure 5. Depth phase arrivals at regional and near-teleseismic distances as a function of epicentral distance and event depth. The plot shows the initial distance from an event in which a depth phase (either pPn, sPn, pP, or sP) is theoretically predicted to occur from IASPEI91 (Kennett and Engdahl, 1991) as a function of the event depth. For the near-regional analysis (< 10°) of the AEIC data, we can only detect sPn and pPn phases for crustal events (<35 km), while deeper events may only have the sPn arrival.

Our focus during the past year has been to examine the cepstral F-statistic technique at near-regional distances for small-to-moderate sized events of varying depths. To accomplish this task, we have acquired a high-quality ground-truth dataset compiled by Ratchkovski and Hansen (2001) (henceforth referred to as RH (2001)) using the Alaska Earthquakes Information Center (AEIC) network. We have chosen a subset

(Figure 7) of the 14,000 events they relocated, and we are in the process of applying the cepstral F-statistic method to the seismic data recorded for these events at regional distances. Data recorded from the Alaskan stations/arrays ATTU, BCAR, BMAR, KDAK, ILAR, and IMAR (Figure 6) are being used in the analysis to determine depth phases, and we are comparing the cepstral depth phase detections at regional distances with depth phase detections recorded at teleseismic distances (PDAR, MNV, and YKA). Preliminary results of these analyses are presented in the following paragraphs.

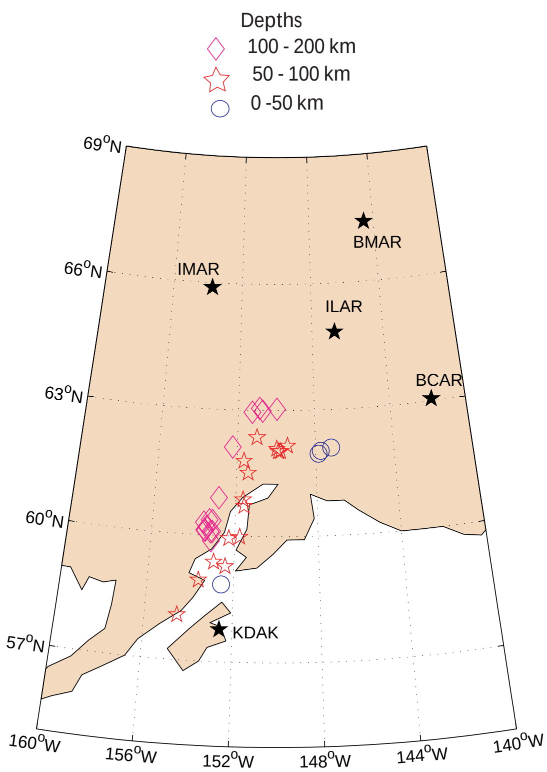

Figure 6. Subset of events from the Ratchkovski and Hansen (2001) database for use in cepstral F-statistic studies at near-regional (black stars) 3-C stations or arrays. The shape of the Alaskan-Aleutian subduction zone can be inferred from the deepening of earthquakes toward the west.

Table 1 provides source data for an event from the RH (2001) subset for which regional cepstral analyses are ongoing. Evid 14888 is a crustal event occurring at 40 km depth in central Alaska. The event was recorded on BCAR, BMAR, ILAR, IMAR, and KDAK (all shown in Figure 7) together with YKA in northern Canada. Data from each event was downloaded from the United States National Data Center, and the cepstral F-statistic analyses were performed (Figure 7). Data at KDAK and IMAR were poor quality and were not used. Several arrays have cepstral F-statistic detections that align with theoretical arrivals for the depth phases calculated using the RH (2001) depth. At BCAR, a peak that rises slightly above the 99% confidence interval aligns with *pPn* while at ILAR (Figure 8), large peaks are noted for both *pPn* and *sPn*. At BMAR, there is a peak just below the 99% confidence level that correlates with the predicted *pPn* arrival, and if the level was reduced to 95%, the peak would have been marked as a detection as would additional peaks that do not correspond to depth phases. Based upon our analyses, the ILAR data provides the strongest argument in support of the RH (2001) depth determined for this event. The number of peaks in the cepstral F-statistic is greatly increased in the regional analyses as compared to the far-regional and teleseismic applications. We believe that the manner in which we have used the technique here as a secondary tool for verification of network calculated depths may be the most appropriate application of the cepstral F-statistic at regional distances.

EVID	YMD	Origin	Long	Lat	Depth	Mag
14888	980115	05:59:04	-147.74	62.04	39.67	4.1

Table 1. Events from the RH (2001) database discussed in this paper.

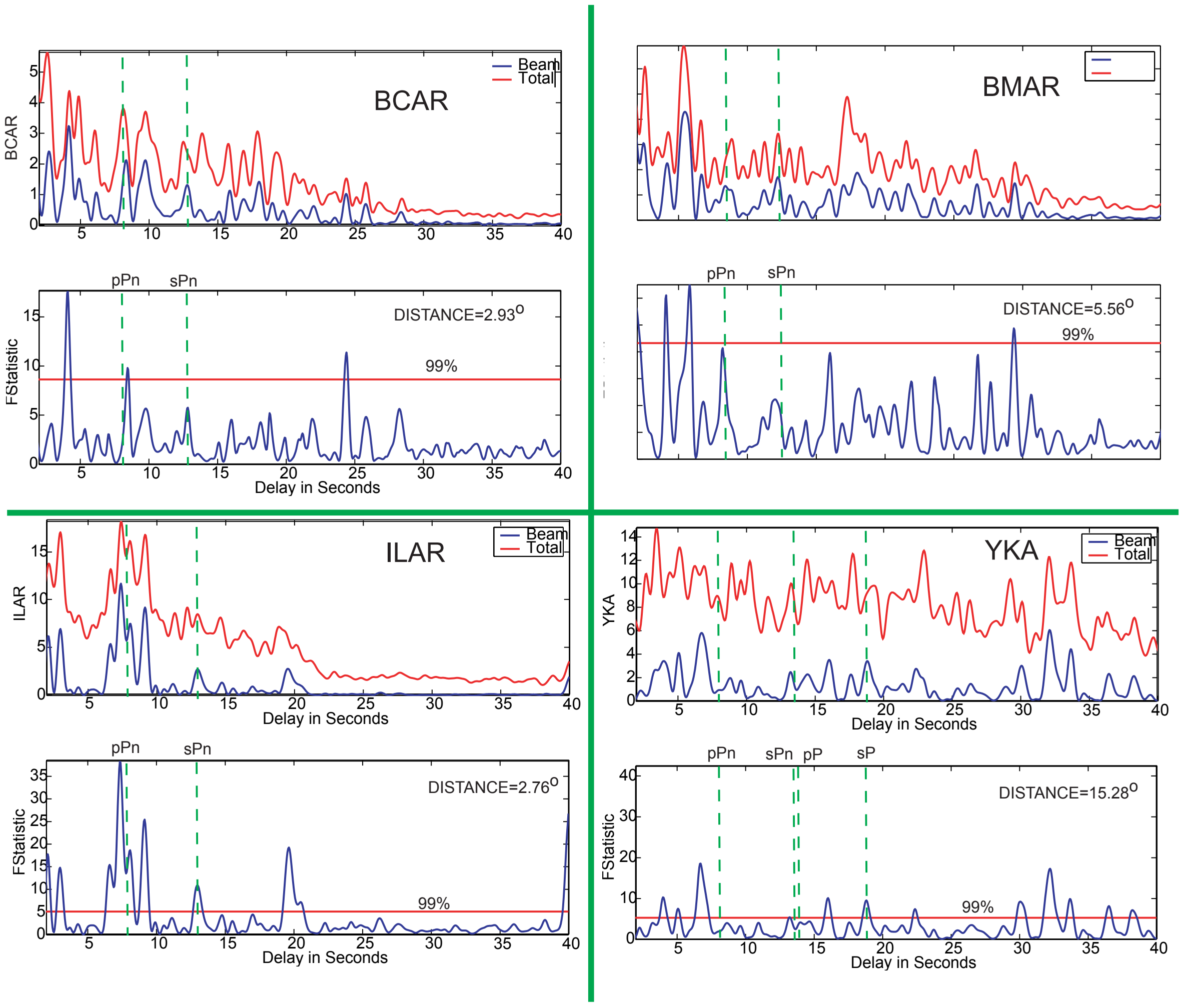

Figure 7. Cepstral F-statistic analyses on regional data recorded at BCAR, BMAR, ILAR, and YKA for event 14888 (Table 1). In the upper plot of each station analysis, the total cepstrum and beam cepstrum are presented. In the lower plot, the cepstral F-statistic is shown together with the 99% confidence level. In each plot, the x-axis represents the delay time (in seconds) between the depth phase candidate and the P wave arrival. The epicentral distance and the predicted arrival times for the depth phases based upon the RH (2001) depth are also provided.

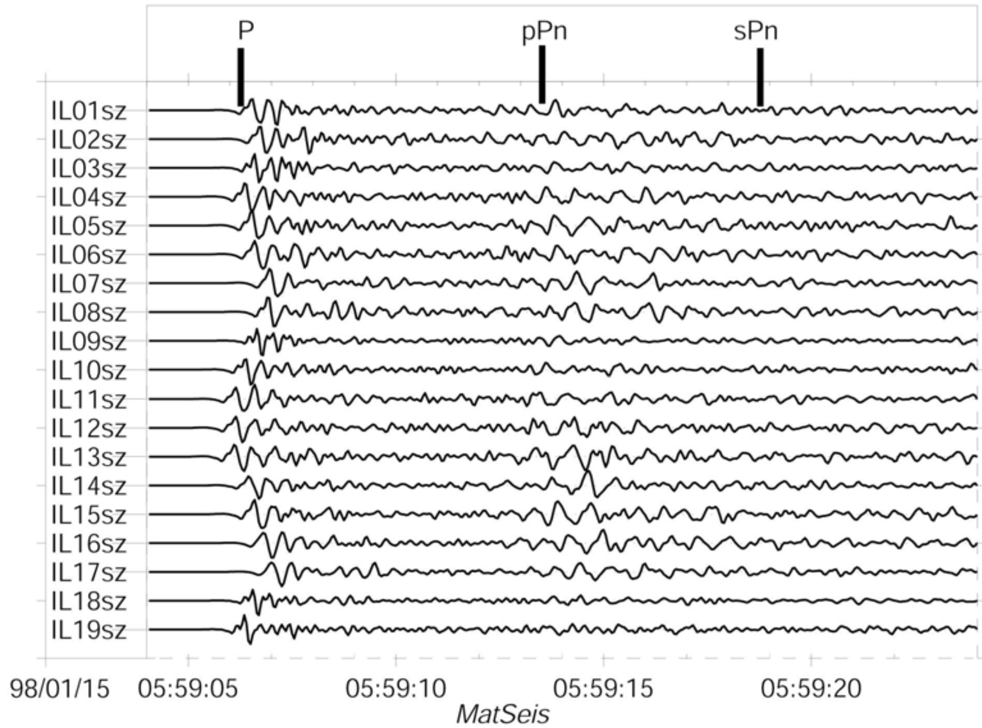

Figure 8. ILAR data for Evid 14888 with the cepstral F-statistic peaks at 7.7 and 12.7 seconds denoted as pPn and sPn, respectively

CONCLUSIONS AND RECOMMENDATIONS

The goals of this study were to determine a statistical parameter to accompany cepstral peaks in seismic data, and to determine if cepstral methods could be incorporated into the daily processing routines at a data center. We have formulated a cepstral focal depth estimation technique that provides a statistical estimate of the significance of the peaks in the stacked cepstrum. This significance measure, which we have termed the cepstral F-statistic, has been missing in previous cepstral estimates of focal depth. We have applied this method to synthetic data and found that the method will detect depth phases with SNR greater than 2 to 4 when the *P* wave SNR is greater than 5 to 8. We have tested the method on USGS, pIDC, and IDC datasets and shown that the method is more reliable at picking possible depth phases than current detection algorithms. We suggest that the Murphy *et al.* (1999) method of network stacking of post-*P* detections be extended to include cepstral F-statistic detections, thus providing an automated method of translating cepstral peaks to seismic event depths. Our results suggest the method is best applied at epicentral distances greater than 12° where *pP* and *sP* are the most commonly observed depth phases. Near-regional analysis is more difficult to accomplish in an operational setting because of the complexity of regional seismograms and the nature of the ray paths for *pPn* and *sPn*. As this research program draws to a close, we plan to begin implementing the program and results into the CMR R&D test bed for additional testing and algorithm development with a goal of including the technique in a future release of IDC software. Our recommendation is for use of this technique in an operational setting such as the United States National Data Center (USNDC), the International Data Center (IDC) and NEIC as a tool to aid an analyst in determining a depth for an event. For teleseismic data, the method can be used in parallel with the standard processing techniques with cepstral F-statistic detections being fed into a network-stacking algorithm for a preliminary depth determination. The analyst could then use the results to verify the existence of the depth phases suggested by the cepstral analyses. For regional data, we suggest a different application. After a preliminary depth has been determined using standard location techniques with network phase arrival time data, we propose that the cepstral F-statistic technique could be implemented on the regional network data for the event. The peak detection methods would help highlight any possible depth phases that could then be used to verify or alter the initial network-calculated depth. By employing techniques such as the cepstral F-statistic method, statistically valid depths can be assigned to events that only a few stations recorded, leading to more confident event screening. Also, depth determination independent of a network solution will lead to more accurate and reliable event locations, since the depth calculated from the cepstral F-statistic method can be used to constrain a hypocentral solution.

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