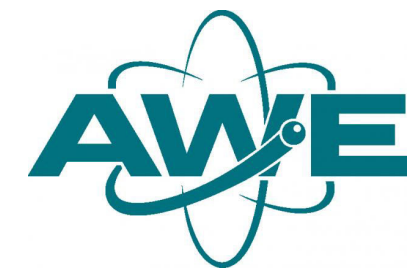


Static Corrections to Improve Detection, Location and Measurement of Seismic Discriminants at IMS Arrays

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- Seismic arrays form an important part of the International Monitoring System
- Need to **detect**, **locate** and **distinguish** potential underground nuclear explosions from naturally-occurring earthquakes
- We present a semi-automated procedure to calculate corrections to the **backazimuth** and **slowness** for seismic energy arriving at an array
- We also calculate **static corrections** to the **relative arrival time** and **amplitude** of the waveform for each seismic station in the array
- The resulting stacked waveform has **enhanced signal-to-noise ratio** useful for forensic seismology

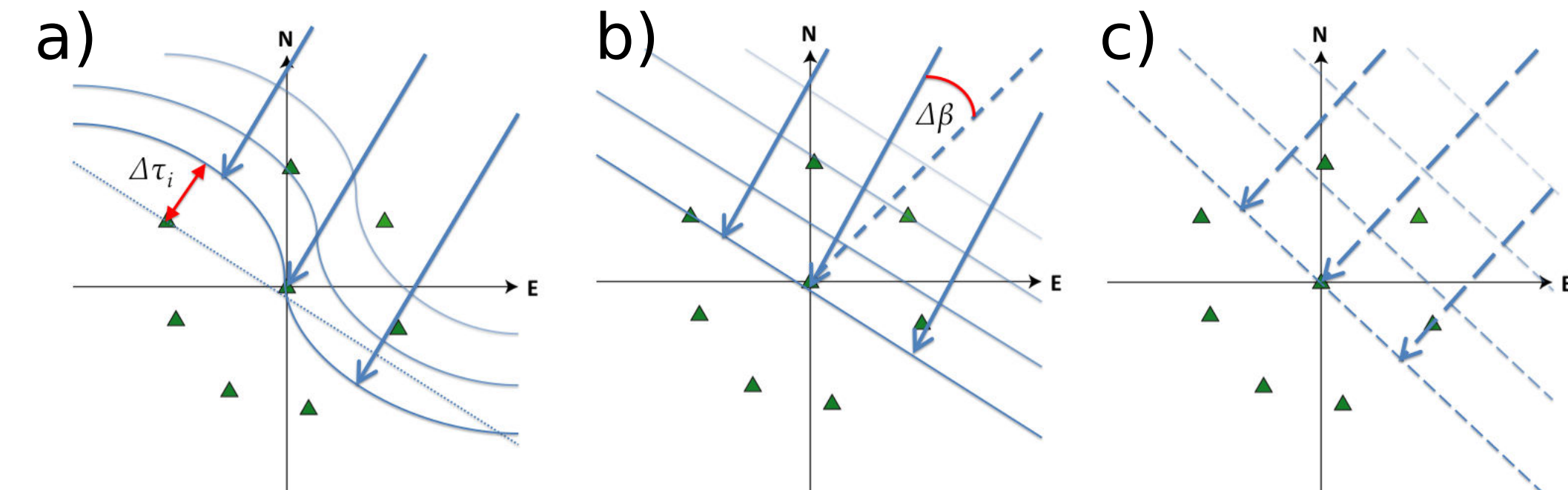
Methods and Techniques

Slowness-azimuth station corrections (SASCs) to the backazimuth and horizontal slowness of the incident seismic energy are calculated using frequency-wavenumber (FK) analysis^[1]. The FK analysis is performed on a 20 s time window around the model-predicted (*ak135*) P arrival, in the 0.5–5.0 Hz frequency band for a slowness range of -0.1–0.1 s / km.

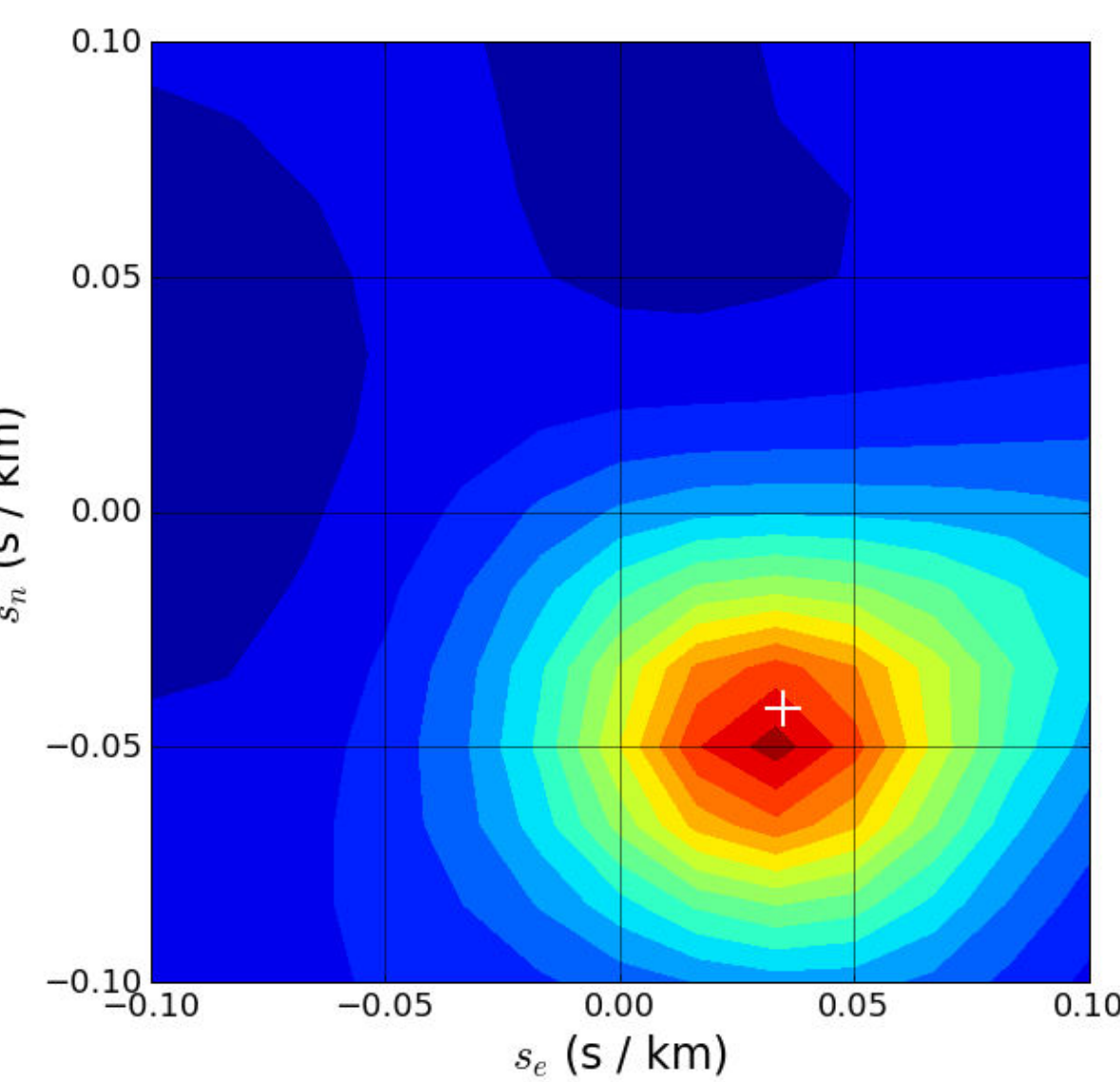
The F-statistic^[2] is used as a measure of signal-to-noise ratio (SNR) and as a detector for identifying the slowness vector where the signal energy is maximised. The power in the slowness-stack for each point in the FK grid is used to calculate the F-statistic, and the slowness and backazimuth where *F* is maximum is taken as the observed slowness vector of the P arrival.

The corrections to the model-predicted slowness are then used to compute an improved linear stack as a signal template across the array.

Seismic traces from each individual station are cross-correlated with the improved stack (minus the contribution from that station) to measure accurate delay times and relative amplitude scalings for that station. These can then be used as static corrections to further improve the SNR, as measured by the F-statistic.



The corrections are made in two stages. In a) we have the uncorrected wavefront travelling across the array. The static corrections for each station align the arrival of the P phase at each station as if it were a plane wave. This plane wave b) also requires a slowness-azimuth correction to give more accurate delay times when creating the linear stack compared with the initial velocity model.



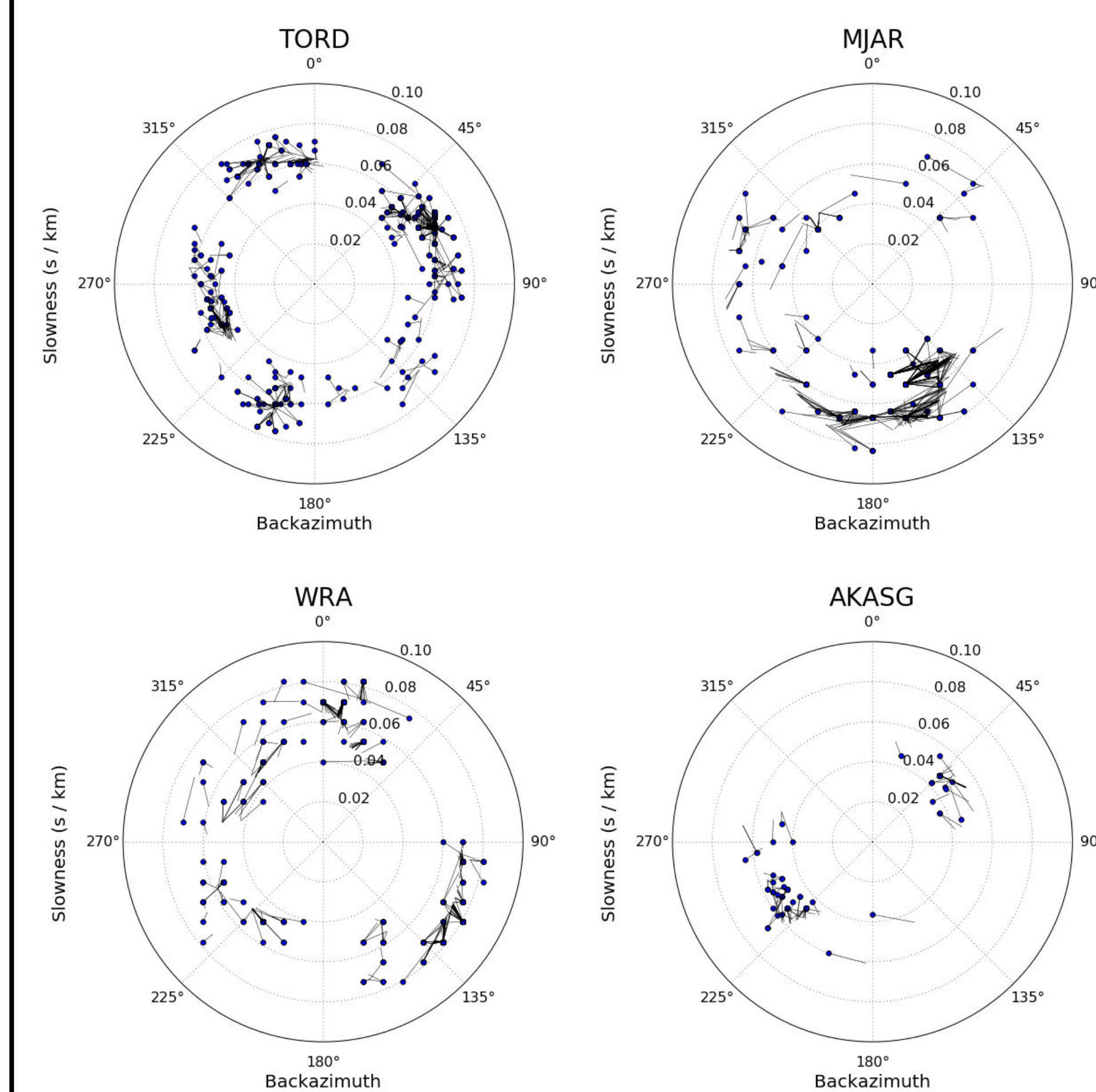
$$F = \frac{N(N-1)\hat{u}(t)^2}{\sum_{i=1}^N u_i(t)^2 - N\hat{u}(t)^2}$$

where:-
 $u_i(t)$ is the time series data from the *i*th station in the array
 $\hat{u}(t)$ is the stacked time series data.

The numerator represents the power in the stack, which is used as an estimate of the signal. The denominator is the summed power in the raw data minus the stack, representing the noise power.

Above is an example FK plot for a $m_b = 5.2$ event recorded at MJAR at a distance of 71° . The velocity model predicts a (slowness, backazimuth) of (0.054 s / km, 130°) marked as a white cross. The FK analysis gives maximum *F* at (0.060 s / km, 146°). The slowness and azimuth residuals become the SASC for the event.

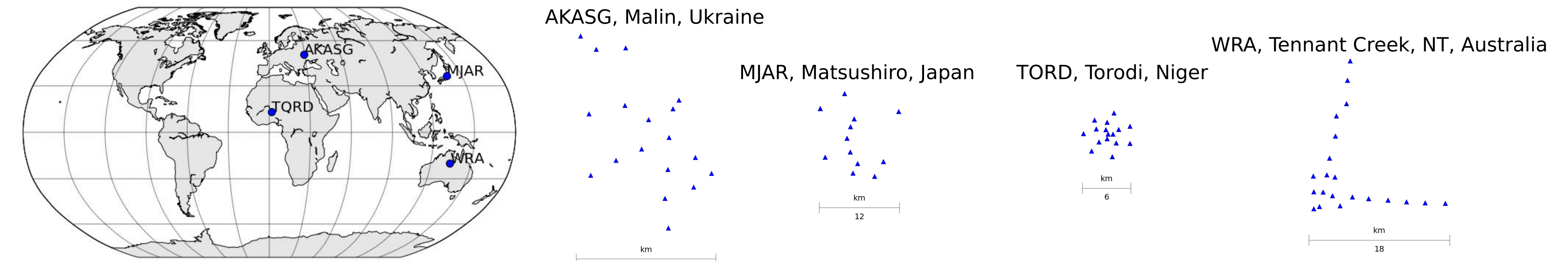
Slowness-azimuth Corrections



Mislocation vectors^[5] for the four arrays. The blue circles show the slowness and backazimuth observed in the FK analysis. The line points towards the observed slowness and backazimuth from those predicted by the *ak135* velocity model.

Data and Arrays used in this study

This technique was applied to four IMS primary broadband seismic arrays: AKASG, MJAR, TORD and WRA:-



The data come from teleseismic events of magnitude $m_b \geq 4.5$ in the epicentral distance range $50-80^\circ$, giving P arrivals with expected slowness of 0.06–0.08 s / km (6.5–9.0 s / °). For each array, a catalogue of 800 (TORD) and 1600 (others) such events was produced and used in the FK analysis to find SASCs. Events were rejected if the FK analysis produced a backazimuth correction in excess of 30° or a slowness correction in excess of 0.01 s / km (~15%), generally seen only for events with very low initial SNR. Static corrections were rejected if the time shift found in the cross-correlation was > 5 s as this was unlikely to be matching the same arrival between the station and the stack. As routine pre-processing, seismic traces were Butterworth-filtered between 0.5 and 5.0 Hz prior to the FK analysis, and cosine-tapered to a time window beginning 10 s before and ending 60 s after the model-predicted P-arrival when performing the cross-correlation to find the static corrections.

Static Corrections

The right-hand plot shows linear stack time series data and F-statistic (2 s moving time window) from MJAR for two events. Each plot shows a different stack using: a) uncorrected *ak135* travel time predictions, b) slowness and azimuth corrections applied across the array, and c) static corrections to the delay time and amplitude applied at each station.

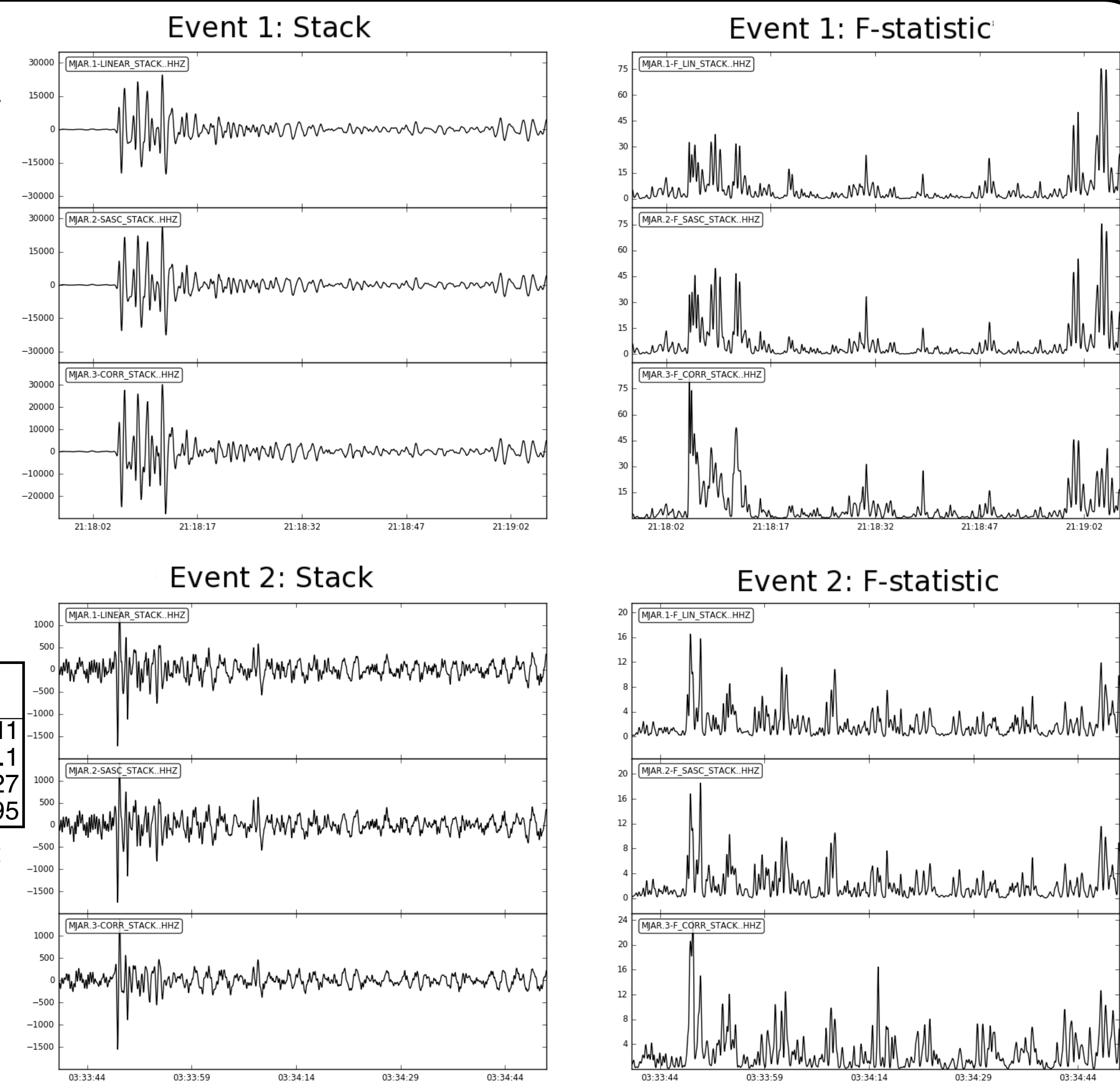
Event 1: $m_b = 6.4$, distance = 70.2° , prior backazimuth = 132° , backazimuth correction = 16° , slowness correction = $-1.5e-3$ s / km

Event 2: $m_b = 4.5$, distance = 71.6° , prior backazimuth = 134° , backazimuth correction = 0.68° , slowness correction = $-6.6e3$ s / km

The table below shows the number of events (after quality control – see Data section above) that showed an improvement in F-statistic after the corrections were applied, the mean % improvement in *F* (ΔF_{max}), and the standard error in the mean % improvement ($\sigma_{\Delta F_{max}}$).

Station	Statics			SASCs only		
	# events	ΔF_{max}	$\sigma_{\Delta F_{max}}$	# events	ΔF_{max}	$\sigma_{\Delta F_{max}}$
AKASG	25/80	160%	4.7	68/80	63%	1.1
MJAR	144/448	58%	4.7	300/448	18%	1.1
TORD	319/542	71%	6	253/542	4.50%	0.27
WRA	89/380	32%	4.6	274/380	17%	0.95

For ~25% of events that generated corrections that passed the quality control, we observe an increase in the F statistic recorded in a 20 s window around the P arrival. For three of the stations, even where the statics did not improve the F-statistic, the SASCs applied alone achieved an increase in *F* in a majority of events (~70%). At TORD, the static corrections had more events where *F* was increased than the SASCs applied alone.



Conclusions and Future Work

This technique of FK analysis and cross-correlation can be applied to the data from IMS and other seismic arrays in order to generate corrections to the slowness, azimuth, arrival time and amplitude. These corrections can be demonstrated to improve the SNR of the linear stack (as measured by the F-statistic).

We will next use this method to apply static corrections at MJAR and other regional arrays to investigate SNR improvement for the waveforms recorded from previous DPRK nuclear tests, and will make new measurements of seismic discriminants (e.g. regional P/S amplitude ratio^[4]) with the corrected waveform data.

References: [1] Rost, S. and Thomas, C., Array seismology: methods and applications, 2002, *Reviews of Geophysics*, 40(3)
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