

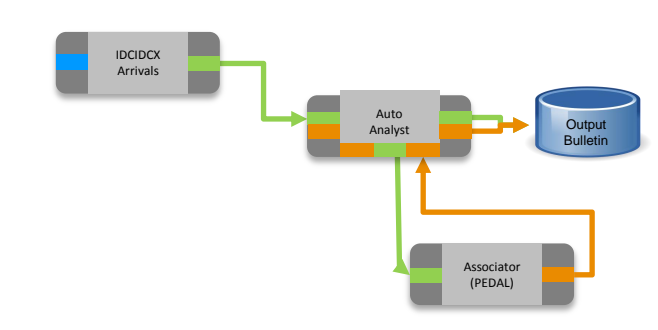
## Overview

The International Data Center (IDC) automatic seismic event bulletin is generated by performing two sequential processing steps: station processing to find detections, and network processing (association) to form events. This processing paradigm differs significantly from that applied by human analysts. Analysts bring to bear considerable intuition acquired during the processing of past events and use that to iteratively reprocess data, resulting in a significantly improved bulletin. Our Iterative Processing Framework (IPF) attempts to mimic analyst behavior during automated bulletin generation, and thereby improve the quality of the automated bulletin.

As shown in Figure 1, IPF consists of several modules. Rather than a pipeline, we have Auto Analyst controlling the processing loops used. Traditional processing is simulated by using IDCICDX arrivals and the Associator. We can also turn on the Waveform Correlation Detections module, or iterate and look for more detections.

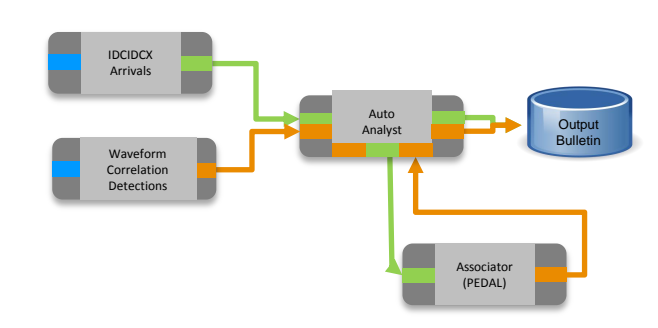
## Pipeline Options

### Option #1 – Baseline: IDCX Arrivals and PEDAL



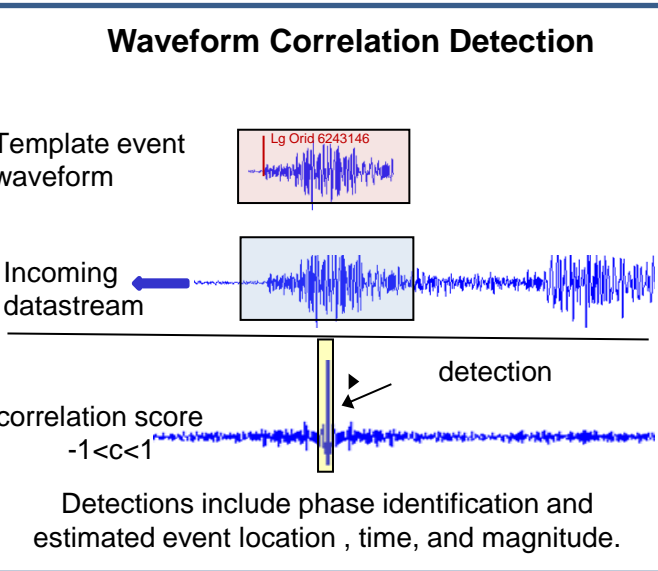
PEDAL is an associator developed at SNL which uses a probabilistic approach to event association (Draelos, 2015). Using the IDCX arrivals as input and PEDAL as associator allows us to obtain a baseline performance for our system. Moreover, we can compare the performance of our associator to the General Associator (GA) used at the IDC. As shown in Figure 2, we see PEDAL has about half as many missed events as GA, while holding the number of false events steady.

### Option #2 – Baseline + Waveform Correlation Detections



In this option, we add in Waveform Correlation detections. Waveform Correlation Detection uses the waveforms of historical events to detect similar events in the incoming data stream. It has been shown to detect events about 1 magnitude unit smaller than traditional detection (Schaff, 2010) and is adept at detecting events in noise or coda. Waveform correlation detections are sent to Auto Analyst with associated metadata (estimated origin time, estimated latitude/longitude, estimated magnitude, estimated phase). PEDAL adds these detections to its pool of arrivals, then forms events.

- WC Detections improve the bulletin output by improving the input to PEDAL:
- Includes arrivals in noise or coda that were missed by sta/ta
  - Arrivals have (correct) phase identification and an estimated event location, which aids the associator



For this work we have used waveform correlation at several key stations: MKAR, ZALV, BVAR, CMAR, PDAR, TXAR, ARCES, FINES, BOSA. We anticipate performing waveform correlation at all IMS primary stations would improve results further.

This module can be tuned to optimize for desired tradeoff between missed and false events. Tuning parameters include correlation thresholds and template selection. Waveform correlation detections can be passed directly to PEDAL, or first be validated through multi-station validation (shown as ndef >1).

References: Schaff, D. P., & Waldhauser, F. (2010). One magnitude unit reduction in detection threshold by cross correlation applied to Parkfield (California) and China seismicity. *Bulletin of the Seismological Society of America*, 100(6), 3224-3238.

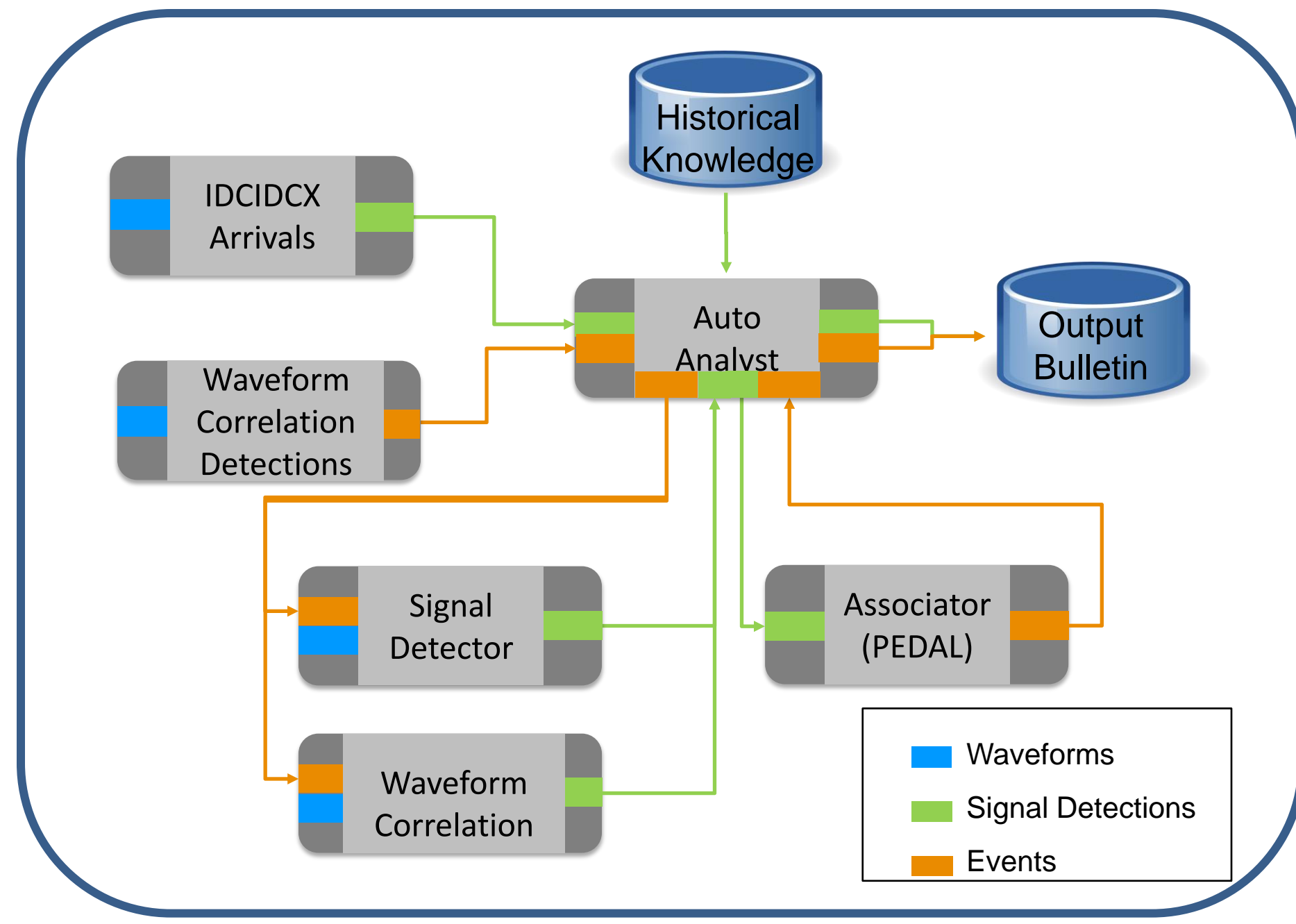


Fig 1: Iterative Processing Framework

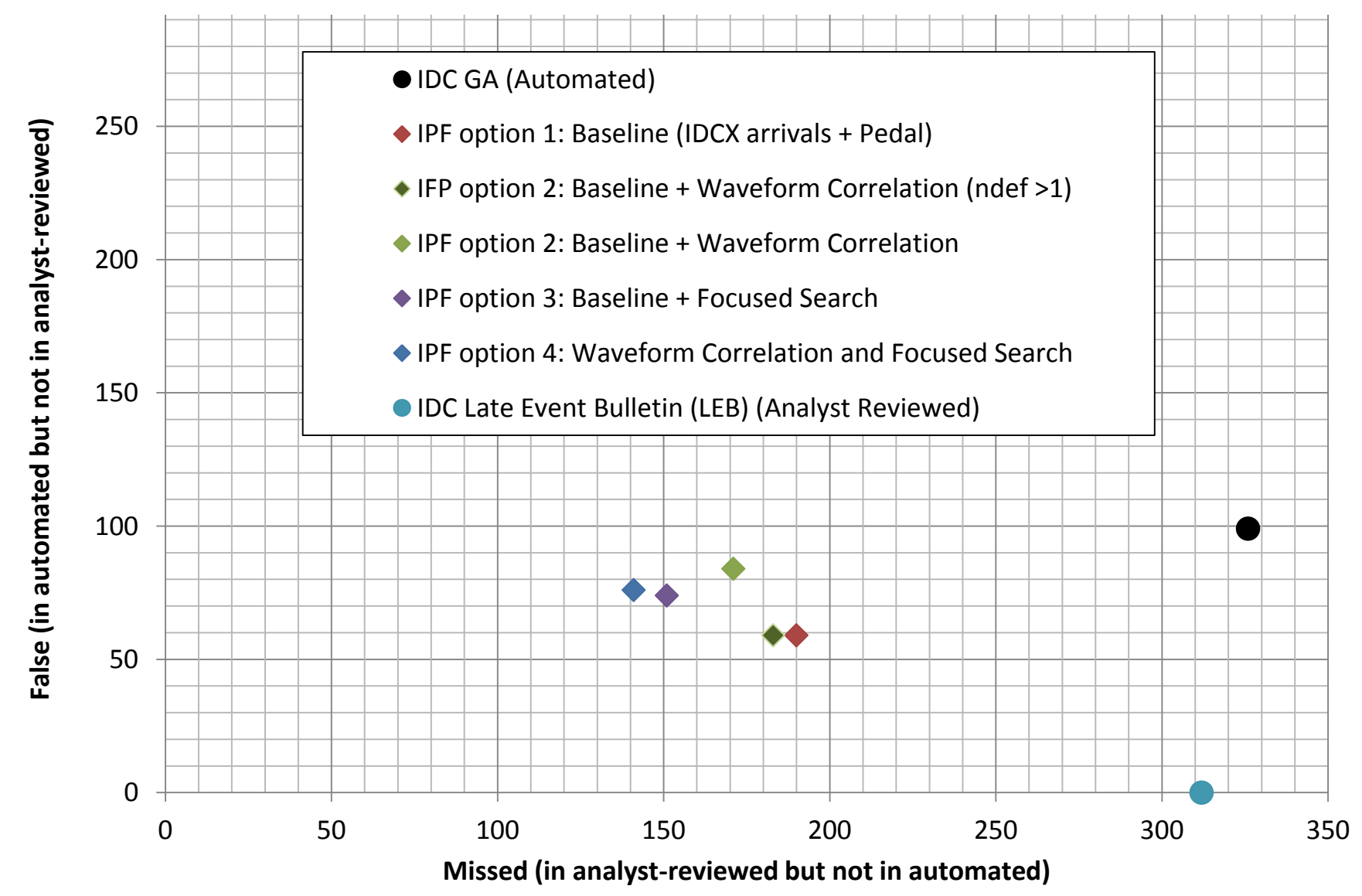
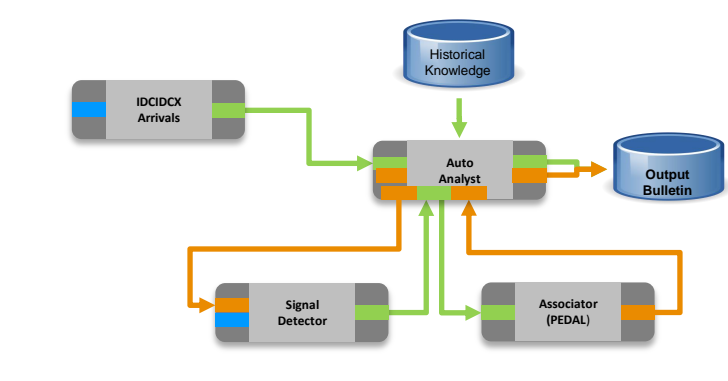


Fig 2: IPF results compared to analyst-reviewed bulletin. Results for May 15 – 17, 2010. There were 817 events in the analyst-reviewed bulletin.

## Option #3 – Baseline + Focused Search



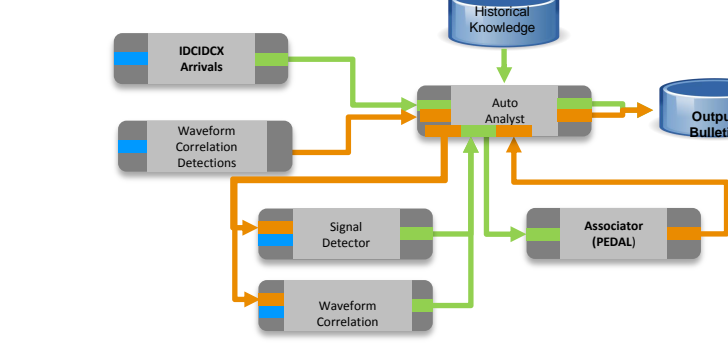
Here we turn on iteration, using Auto Analyst (with its access to historical information) to decide when to reprocess stations (to search for expected, but missing, arrivals). For example, Auto Analyst may notice that an event built by PEDAL doesn't contain an arrival from a station that is located nearby and usually contributes to events built in that region. It can launch a Focused Search and run our signal detection WavePro at that station. At the expected arrival time WavePro searches for the missing arrival using a lowered detection threshold.

Incorrect azimuth and slowness estimates are often at the root of unassociated arrivals. WavePro performs FK analysis on a variety of windows and filterbands, mimicking how an analyst behaves. Then it clusters the results and chooses the best option, yielding improved azimuth and slowness estimates for the detection. Detections from Focused Search are fed back to PEDAL, which rebuilds the bulletin.

- Focused Search improves the bulletin output by:
- Identifying likely missed arrivals, and finding low SNR arrivals
  - Correcting azimuth and slowness estimates
  - Finding corroborating evidence for high quality detections seen at a single station, allowing those events to be included in the bulletin (which requires events to have arrivals at 2+ stations)

This module can be tuned by modifying the FK algorithm and changing parameters for WavePro detections.

### Option #4 – Waveform Correlation Detection + Focused Search



This option exercises all modules of IPF, using waveform correlation detections and allowing focused search. In addition to the benefits detailed in Option #2 and Option #3, turning on all modules improves the bulletin output by:

- Using the location and arrival time meta-data from WaveCorr detections to guide Focused Searches
- Finding corroborating arrivals at additional stations for single-station WaveCorr detections.

## Experiment Setup and Results

Our results from these preliminary tests show clearly that modifications to the pipeline system can substantially improve automated bulletin generation. We ran each version of IPF for May, 15 – 31, 2010. We compared output bulletins by comparing each IPF-bulletin against our analyst-reviewed bulletin. Our analyst-reviewed bulletin was generated by an experienced analyst who took the LEB as a starting point, then reviewed the IPF detections and added new events which he determined to be valid. This enhanced bulletin was completed for only May 15-17, 2010, due to the time consuming nature of this work. Events were categorized as valid (in both bulletins), missed (in the analyst-reviewed bulletin but not in the IPF bulletin), or false (in the IPF bulletin but not in the analyst-reviewed bulletin). There is a natural tradeoff between missed and false events; the penalty for missed events is much higher than for false events in the monitoring scenario.

- PEDAL performs significantly better than GA. IPF Option 1 had significantly fewer missed and false events compared to IDC GA; the number of missed events from decreased by 136 and the number of false by 40.
- Adding Waveform Correlation Detections leads to additional events with no increase in false events (dark green), with the option to trade off further reducing missed events in exchange for some false events (light green).
- Adding Focused Search reduced the number of missed events considerably
- Comparing IPF option 4 to option 1, we see the benefits from adding in Waveform Correlation and Focused Search. These preliminary results show 50 fewer missed events while only adding 17 events not in the bulletin.

## Future Work

- Next we intend to obtain results for all of May, 2010, once our analyst-reviewed bulletin is complete.
- Add waveform correlation detections from all IMS stations, and tune to reduce false detections.
- Add false event screening