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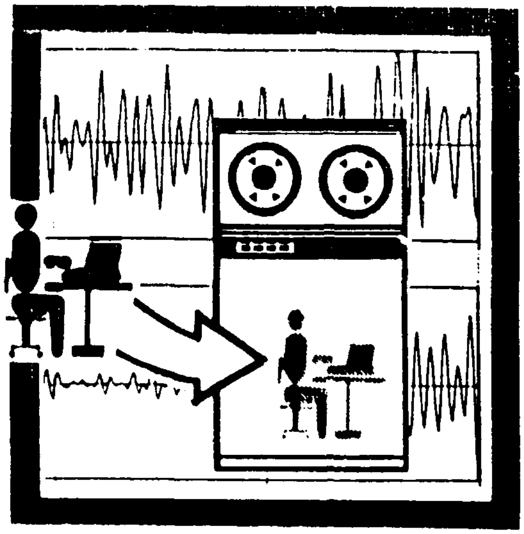

INTELLIGENT ARRAY SYSTEM

by

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W.E. Farrell, R.F. Fung[2] J.W. Given, A.S. Henson,
C. Kobryn, H.J. Swanger, J. Wang

FINAL TECHNICAL REPORT
October 1990

Science Applications International Corporation
10260 Campus Pt. Drive
San Diego, CA 92121

Sponsored By:
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Order Number 5504, Amendment #1
Monitored by:
Dr. Ralph Alewine
DARPA/NMRO

Contract No. MDA903-87-C-0037
Principal Investigator:
Dr. Thomas C. Bache
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Approved for Public Release
Distribution Unlimited

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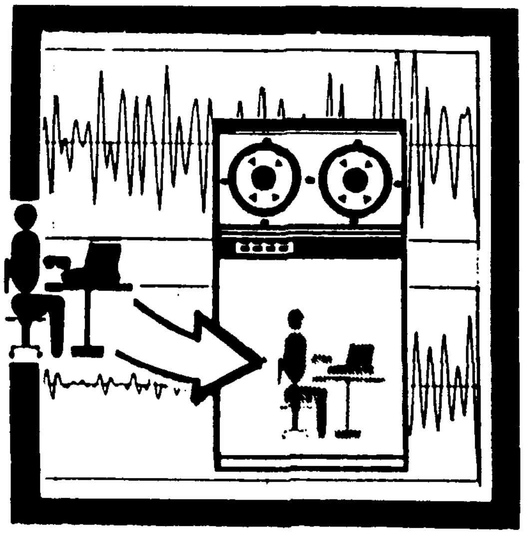

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Table of Contents

ABSTRACT

This final technical report includes a short Executive Summary which summarizes important management and administrative aspects of this 42-month project, including a brief chronology and an accounting for the funds by major cost category. The rest of the report presents a detailed description of the major product of this project, a computer hardware/software system called the Intelligent Array System (*IAS*). The *IAS* processes data from two high-frequency arrays (NORESS & ARCESS) in Norway to detect, locate and identify seismic events. The *IAS* computers and functions are distributed between the NORSAR Data Analysis Center (NDAC) near Oslo and the Center for Seismic Studies (Center) in Arlington, VA. The *IAS* modules at NDAC automatically retrieve data from a disk buffer, detect signals, compute signal attributes (amplitude, slowness, azimuth, polarization, etc.), and store them in a commercial relational database management system (DBMS). *IAS* makes scheduled (e.g., hourly) transfers of the data to a separate DBMS at the Center. Arrival of new data automatically initiates a "knowledge-based system" (KBS) which interprets these data to locate and identify (earthquake, mine blast, etc.) seismic events. This KBS uses general and area-specific seismological knowledge represented in rules and procedures. For each event, unprocessed data segments (e.g., 7 minutes for regional events) are retrieved from NDAC for subsequent display and analyst review. The interactive analysis modules include integrated waveform and map display/manipulation tools for efficient analyst validation or correction of the solutions produced by the automated system. Another KBS compares the analyst and automatic solutions to mark overruled elements of the knowledge base. Performance analysis statistics guide subsequent changes to the knowledge base so it improves with experience.

The *IAS* is implemented on networked Sun workstations, with a 56kbps satellite link bridging the NDAC and CSS LANs. The software architecture is modular and distributed, with processes communicating by messages and sharing data via the DBMS. The *IAS* processing requirements are easily met with major processes (i.e., signal processing, expert system, DBMS) on separate Sun 4/2xx workstations. This architecture facilitates future expansion.

EXECUTIVE SUMMARY

This is the final report on DARPA Contract MDA903-87-C-0037. This summary describes the important management and administrative aspects of the contract. In particular, we summarize the chronology of the contract effort and relevant events that occurred before and after this contract. Also, we summarize the allocation of funds by major cost categories.

The technical report that follows this EXECUTIVE SUMMARY is a detailed description of the major deliverable item produced by this contract, the *Intelligent Array System.* The organization of this report is described in Section I ("INTRODUCTION"), particularly Section 1.4 ("Document Organization").

CHRONOLOGY

RELEVANT PRE-CONTRACT EVENTS

1 Jan 86 Phase I Seismic Array Signal Processing System Proposal
SAIC and subcontractor Advanced Decision Systems (ADS) proposed (in response to DARPA/DSS-W RFP MDA903-86-R-0023) a six-month project to design a computer hardware/software system to detect, locate, and characterize seismic events using data from a network of small arrays.

1 Mar 86 SAIC & ADS Phase I Contract Begins
Two Phase I contractors were selected, with the other team being Ensco and subcontractor Teknowledge Federal Systems (TFS). The SAIC funding was $350,000 under Contract MDA903-86-C-0074.

Sep 86 Phase I Completed
SAIC & ADS submitted the "Phase I Final Report and Phase II Implementation Plan" which served as a proposal for the contract now completed with this Final Report. A two-day briefing summarizing this 375 page design description and project plan was presented to a DARPA selection panel, including computer demonstrations of prototypes of key system elements.

26 Nov 86 Selection and Proposal Revision
SAIC was selected as prime contractor and directed to submit a revised proposal including a subcontract for complementary tasks to be done by Ensco (with TFS as subcontractor to Ensco). The first task in the project was directed to be development of a revised plan to include these complementary tasks.

CONTRACT CHRONOLOGY

1 Jan 87 Pre-Contract Cost Authorization
Limited effort began on DSS-W authorization to accumulate some pre-contract costs that would be allowable should final contractual agreement be reached."

1 Apr 87 **Effective Date of Contract MDA903-87-C-0037**
The contract was funded at $5,061,601 for 24 months (ending 31 March 1989), including $1,440,979 for the directed subcontract to Ensco/TFS. The funded system was to acquire its data from an interface at the Center for Seismic Studies (i.e., transmission to the Center was external to the system).

22 Oct 87 **DSS-W Directs Changes to the Scope of Work**
The effort under several tasks was expanded to include R&D to be conducted by research staff resident at the Center for Seismic Studies.

9 Feb 88 Proposal for Changes to Scope of Work
SAIC submitted a proposal specifying the cost for the directed changes listed above and a number of other extensions to the scope of work on the contract.

Jun 88 Contract Modified and Extended
The change proposal was funded with tasks as follows: (1) R&D by Center staff (as directed in October 1987); (2) Move the data interface to the NORSAR facility (requiring additional computers and software and the acquisition, installation, and maintenance of a telemetry link to Norway); (3) Installation of a situation room at the Center (primarily construction, but includes some software); (4) Development of an "Executive Review Station" to summarize results for off-site executives; (5) Integration of a capability to display and manipulate satellite imagery from SPOT; (6) Additional effort to acquire seismological knowledge to be added to the system; (7) Publication of a quarterly newsletter (*The Monitor*) summarizing new technology advances in the NMRO program. To complete these tasks the contract was extended to 30 September 1989. The modified contract was funded at $7,805,620 for its 30-month duration.

30 Sep 89 Delivery of *IAS* to Center for Seismic Studies
The *IAS* is the major deliverable on this contract, and it was delivered in final form by the scheduled end of the contract.

Sep 89 Performance Extension for 12 Months
SAIC requested and was granted a 12-month extension to the period of performance of the contract at no cost to the government. This extension was for a modest effort to complete the "Executive Review Station" and some other minor tasks.

30 Sep 90 Official End of Contract MDA903-87-C-0037
This Final Contract Report completes all deliverables on the contract.

RELEVANT POST-CONTRACT EVENTS

1 Oct 89 *IAS* Operation at Center for Seismic Studies
Under a separate contract, the Center commenced full-time operation of *IAS* on this date. The system was operated continuously for 8 weeks, and the results of this operational test have been published in contract reports and a BSSA paper.

1 Jan 90 *IAS* Delivery to NORSAR
Under a separate contract, *IAS* was delivered to NORSAR. From shortly after this date to the present (October 1990) *IAS* has been operated continuously by the NORSAR staff to produce a bulletin of regional seismicity recorded by the NORESS and ARCESS arrays. *IAS* is used to produce the Norway data contributed to the data exchange experiments conducted under the auspices of the UN Conference on Disarmament.

The reports and papers describing the results produced by *IAS* demonstrate that it represents a substantial advance in the state-of-the-art for seismic data analysis. Further, the operational history indicated by these "post-contract events" demonstrates that the system is robust and economical to operate and maintain.

FUNDING

The estimated expenditure of contract funds (based on costs shown by SAIC accounting plus committed expenditures not yet included) is as follows:[†]

$2,529,938	SAIC system design, software development, system integration, and project management
$1,246,726	Purchase and maintenance (through 30 September 1989) of computer hardware
$ 44,732	Installation of telemetry between the NORSAR Data Analysis Center (NDAC) and the Center for Seismic Studies (Center)
$ 71,855	Lease of communication circuit between NDAC and the Center
$ 927,651	R&D by research staff at the Center for Seismic Studies
$ 98,444	Purchase of imagery from SPOT Image Corporation
$ 327,513	Construction of situation room at the Center (including projectors and sound system)
$ 84,359	Publish four issues of *The Monitor*
$1,440,775	Ensco subcontract (includes subcontract to TFS)
$ 762,638	ADS subcontract
$ 23,550	Inference Corporation subcontract (evaluate application of ART to this problem)
$ 25,000	Columbia University subcontract (upgrade and deliver to the Center a version of the Lamont SunPick program for waveform analysis)
$ 219,152	Administrative costs and SAIC fee for the four subcontracts
-------------	
$7,803,042	Total

[†] In most cases the SAIC fee is included in the total cost. The exceptions are the subcontracts for which we list separately the subcontractor funding and the SAIC administrative costs and fee.

I INTRODUCTION

1.1. BACKGROUND

The *Intelligent Array System* (*IAS*) was developed to meet the data analysis challenge posed by the small high-frequency seismic arrays developed by Norwegian and American scientists in the mid-1980's. The first of these arrays (NORESS) was completed in 1985 and the nearly identical ARCESS array was completed in 1987. Figure 1.1 shows the array locations and geometry (see Mykkeltveit, 1985, Mykkeltveit *et al.*, 1987 for details).

The overall objective for these arrays is to provide an improved capability to detect and identify underground nuclear explosions; that is, an improved seismic monitoring capability. The focus of seismic monitoring R&D since the mid-1960's had been on teleseismic monitoring, in large part due to that stations being sparse or absent at regional distances from areas of primary interest (e.g., the Soviet Union). Also, teleseismic signals are very much simpler and easier to interpret than the complex, high frequency signals seen at regional distances. But several reinforcing factors combined at the beginning of the 1980's to shift the focus toward seismic monitoring at regional distances. Teleseismic monitoring technology had matured to the point that detection and identification capability were reaching their physical limits. At the same time, improved seismic instrumentation and electronics allowed the sensitive recording of the much higher frequencies seen in regional signals, offering the opportunity to exploit this information for event identification. Finally, Soviet resistance to the installation of stations inside their borders began eroding in the late-1970's (during the comprehensive test ban treaty negotiations that were recessed in 1978), and now U.S. stations are being installed in the Soviet Union under scientific exchange agreements. Thus, during the 1980's, detecting and identifying the small events recorded by a regional seismic network became the key technical issue for advancing seismic monitoring capability.

Small aperture regional arrays like NORESS and ARCESS provide a major step forward in seismic data recording technology, since they detect regional signals from all but very small nuclear explosions. For example, a 1 KT nuclear explosion is expected to produce a magnitude of about 2.5, and the NORESS array has been shown to detect 90% of the events of this size occuring to beyond 1000 km (Ringdal, 1986). But signal detection is only the first step, and the real challenge is to use the detected signals to locate events accurately and to distinguish underground nuclear explosions from the many earthquakes and industrial explosions also detected by the network.

The *IAS* provides a new generation of seismic data analysis technology to exploit the full potential of the sensitive new regional arrays. It builds upon work done by the NORSAR staff to adapt and extend well-proven techniques used to analyze teleseismic data from the NORSAR array. A notable accomplishment is the RONAPP program (Mykkeltveit and Bungum, 1984) which processes NORESS data to produce a list of detected signals and located events. RONAPP combines automatic beamforming, signal detection and post-detection (f-k spectrum is most important) processes with a few rules incorporating knowledge about the robust behavior of signals in that region to locate events defined by pairs of associated Pn and Lg phases. This program represents a significant advance in capabilities for automatic production of a seismic bulletin. However, further improvement of the automated processing requires a richer representation of the seismological knowledge used by human analysts and techniques that extend to networks of arrays and non-array stations. *IAS* meets these requirements.

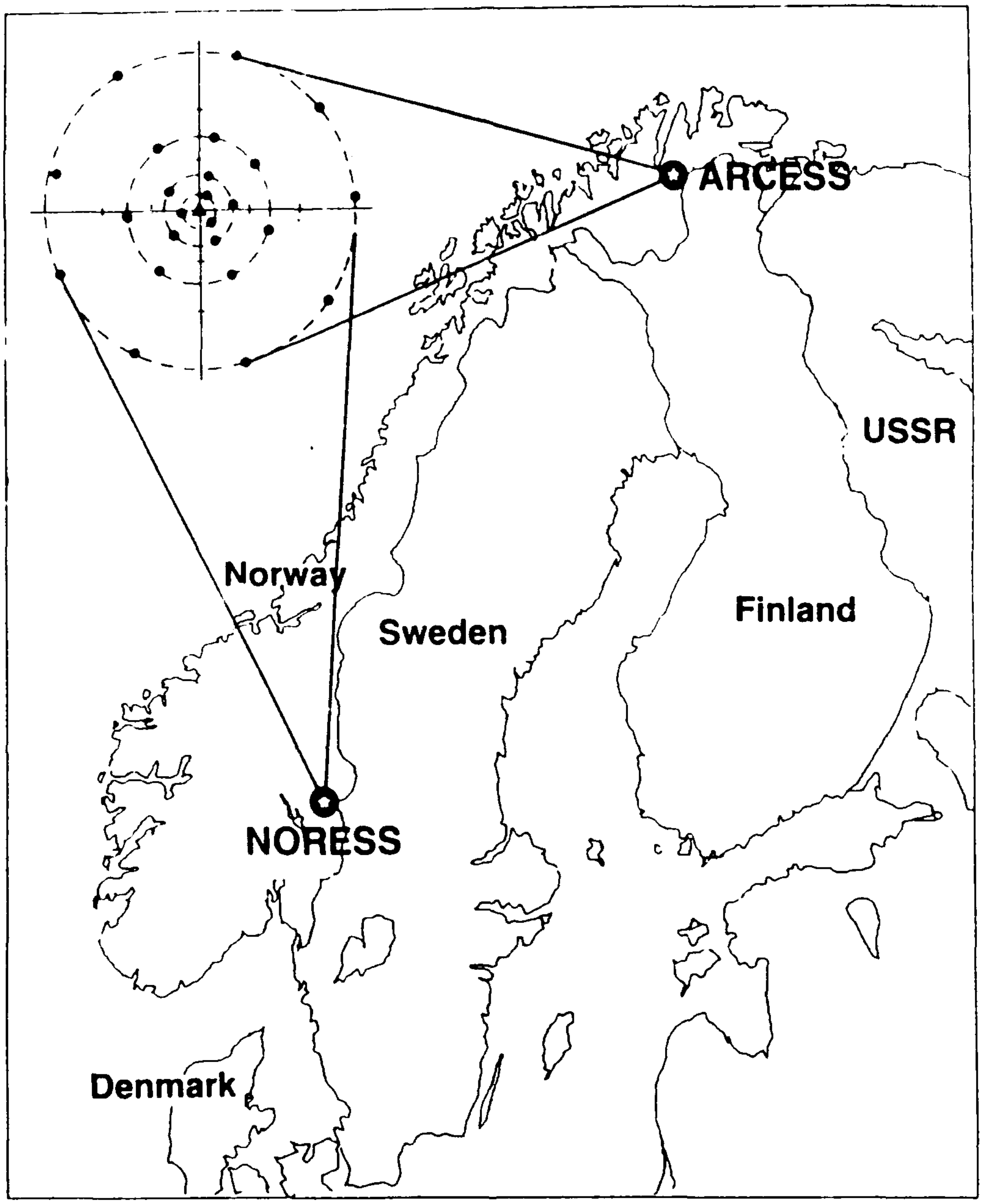


Figure 1.1. The locations and array geometry for NORESS and ARRESS arrays. The two arrays are essentially identical, each having 24 elements in four concentric rings (A, B, C, D) plus a center element (hub). The diameter of the outer (D) ring is 3.0 km. There are 3-component seismometers at the hub and three of the seven sites in the C-ring. (Figure provided by Frode Ringdal, NORSAR)

1.2. CONCEPT

The fundamental concept for *IAS* is illustrated in Figure 1.2. The central element is a computer system which automatically interprets seismic data to detect, locate and identify all interesting seismic events. The automatic interpretation is reviewed and validated by a human analyst. This validation provides a metric for measuring the performance of the "automatic analysis," which is a key part of the concept for acquiring new knowledge to make the system performance match more closely that of the analyst. Also, there are independent R&D activities at many institutions which provide new knowledge and processing techniques that can improve the performance of the automated system.

The purpose of *IAS* is detect, locate, and identify regional seismic events, and (1) the results are to be as reliable as the physics will allow, and (2) the methods are to be as automated as technology will allow. Therefore, the automated processing must represent the complex area-specific knowledge applied by human analysts, and the system must be designed to facilitate the acquisition and incorporation of new knowledge. For these reasons the use of "expert systems" technology is central to the design concept for *IAS*.

1.3. ARCHITECTURE

The overall architecture of *IAS* is shown in Figure 1.3. The raw data from the arrays is automatically recorded and transmitted to the NORSAR Data Analysis Center. At NORSAR the seismic data are separated from the maintenance (state-of-health) data, checked for validity, and stored on a magnetic disk. The *IAS* system then automatically acquires the data from the disk and begins its processing. Since only about 10% of the data include seismic signals, the *IAS* system does the data-intensive signal processing near the source of the data at NORSAR. The knowledge-rich ***interpretation*** is done at the Center for Seismic Studies in Arlington, VA.† The computers are in constant communication across the satellite link between these two sites, much as if they were at the same site. Most of the software development was done at the SAIC facilities in San Diego. Computers at the three sites shown in the figure are linked by a UNIX wide-area network bridge (WAN). This allows nearly transparent access to computers anywhere on the network, and nearly all the software installation and testing at all three sites was done by staff working in San Diego.

1.4. DOCUMENT ORGANIZATION

This introductory section provides a brief summary of the background and motivation for developing *IAS*, the fundamental concept underlying the design, and a high-level view of the overall architecture. A detailed overview of the system is provided in the following sections:

Section II *SYSTEM OVERVIEW*
This provides a conceptual view of the *IAS*. The emphasis is on the "expert system" used for the automated processing and the related elements used to acquire new knowledge to be added to the expert system.

Section III *SOFTWARE ARCHITECTURE*
The individual software modules ("processes") and their interaction are described.

† This is the basic architecture implemented initially. However, an *interpretation* system that essentially duplicates the system at the Center is being installed at NORSAR for independent data interpretation.

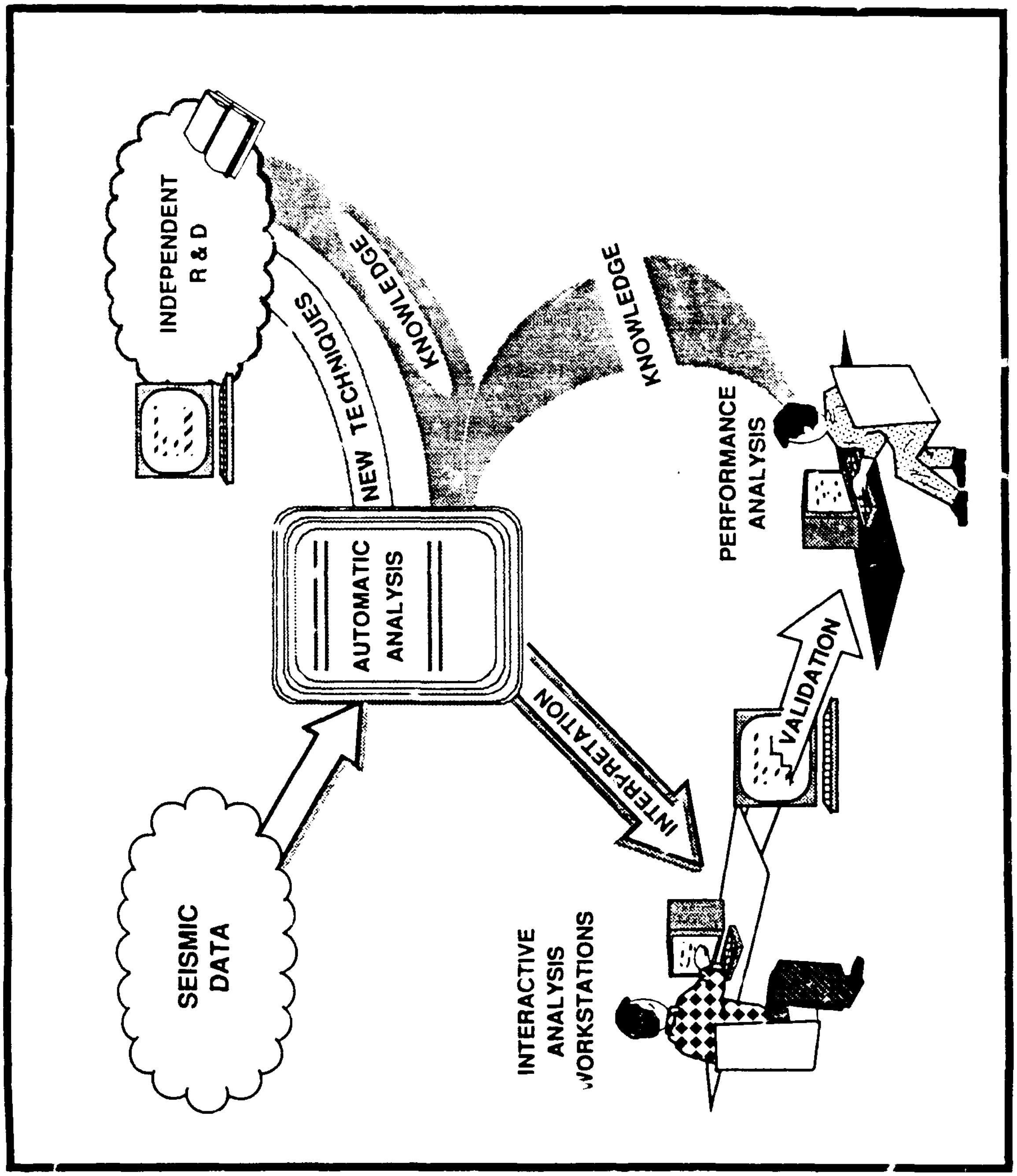


Figure 1.2. The underlying concept motivating *IAS*.

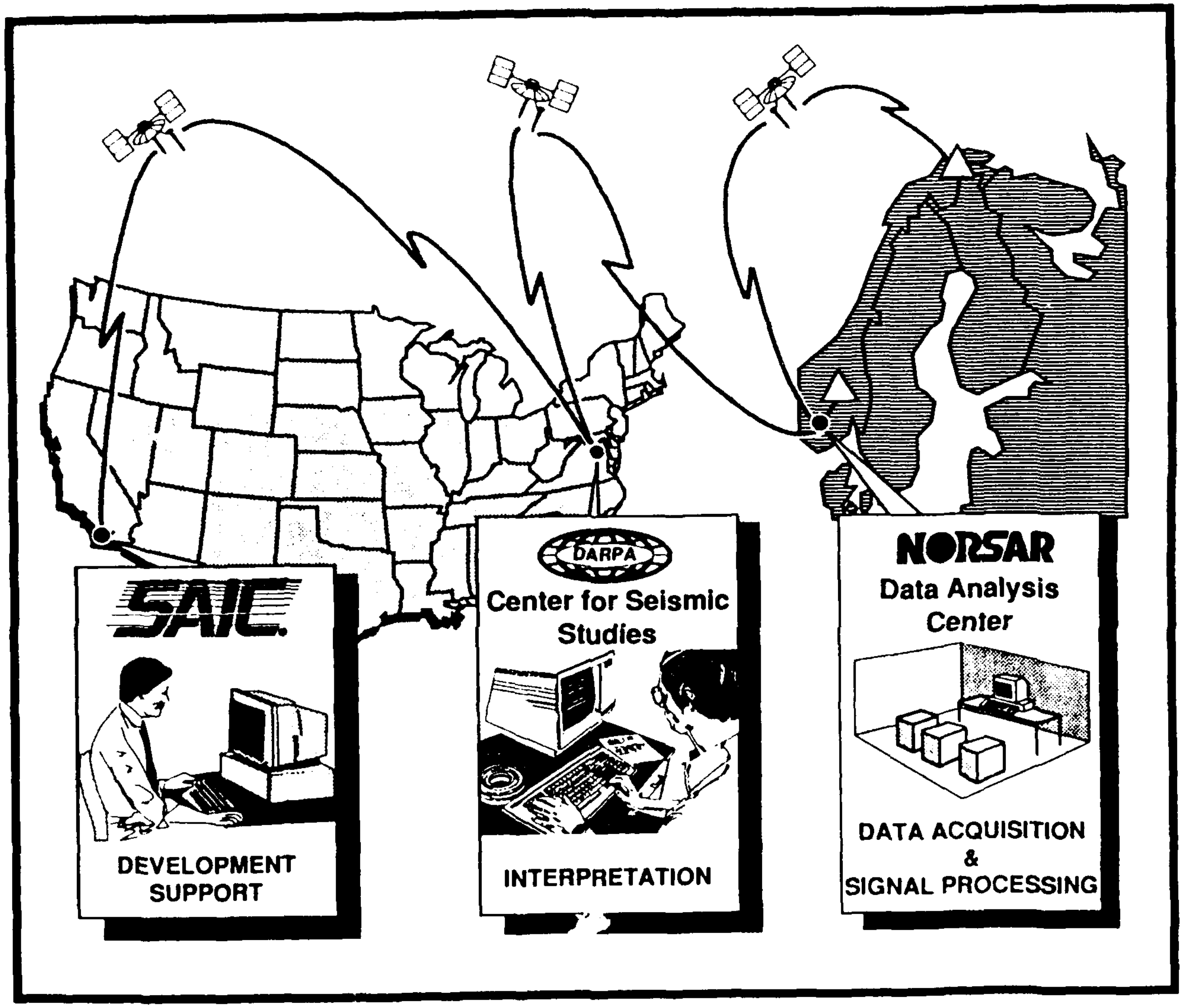


Figure 1.3. The overall architecture of *IAS* is illustrated through the locations of the two arrays that provide data, the three locations involved in the analysis of the data, and the communication links among them.

Section IV *FUNCTIONAL DESCRIPTION*
The system is described from the seismological perspective in this section. That is, we describe the algorithms and rules used for the automated processing and the functions available to a seismologist interacting with the system.

Section V *HARDWARE ARCHITECTURE*
This provides a mapping of the *IAS* software modules to computers.

Section VI *PROCESSING EXAMPLES*
An excellent shortcut to an understanding of the design of *IAS* is a review of the processing examples presented in this section.

II SYSTEM OVERVIEW

2.1. INTRODUCTION

This overview of the *Intelligent Array System* begins with a description of the major software elements of the system in Section 2.2. The central element is the "expert system" which locates and identifies seismic events (Section 2.3). As discussed in Section I, the major reason for introducing expert system technology is to provide a more flexible and convenient framework for introducing the complex region-specific knowledge needed for analyzing seismic events. For this we must acquire the appropriate knowledge in an appropriate form, and our concept for this "Knowledge Acquisition" is described in Section 2.4. We conclude this overview with a somewhat more-detailed view of the overall architecture shown in Figure 1.3.

2.2. MAJOR ELEMENTS OF *IAS*

The major elements of the *IAS* are shown graphically in Figure 2.1. The functional elements are in boxes, and the key data objects are shown between vertical lines. The solid arrows indicate the dominant direction of dataflow. There are also important software facilities that do not fit into a dataflow diagram, and these are shown in the shaded boxes with rounded corners. Each of the elements in Figure 2.1 will now be described.

<u>*Data* (data object)</u>
All seismic data collected by the NORESS and ARCESS arrays are provided to *IAS*. These arrays also transmit state-of-health and engineering data to the NORSAR Data Analysis Center (NDAC) where they are handled by another computer system.† The seismic data are stored on NDAC disks by software developed and maintained by Science Horizons, Inc. and NORSAR.

<u>*Data Acquisition* (functional element)</u>
This software element acquires the data from the NDAC disks as it is needed by elements of *IAS*.

<u>*Signal Processing* (functional element)</u>
The first *IAS* process is to detect signals and extract *features* that describe them. The details of the signal processing are described in Section 4.2. It includes beamforming, signal detection, and arrival time refinement. The segment of data including the detected signal is then processed further to measure the *features*.

<u>*Features* (data object)</u>
Each detected signal is characterized by an arrival time and parameters that describe its character. These parameters describe the amplitude, polarization, and spectrum. The f-k power spectrum is computed and analyzed to estimate the azimuth and slowness of the detected signal. See Section 4.2 for more details about these "post-detection" calculations.

<u>*Event Location* (functional element)</u>
The "expert system" described in Section 2.3 and in more detail in Section 4.3 analyzes the

† As noted several places in this report (e.g., see the discussion of Figure 1.3), there is an intimate link between the computers at the NDAC and the Center that blurs the distinction between *IAS* and non-*IAS* software. For example, the *IAS* system can display graphics produced by other systems at the NDAC simultaneously with graphics produced by *IAS* software.

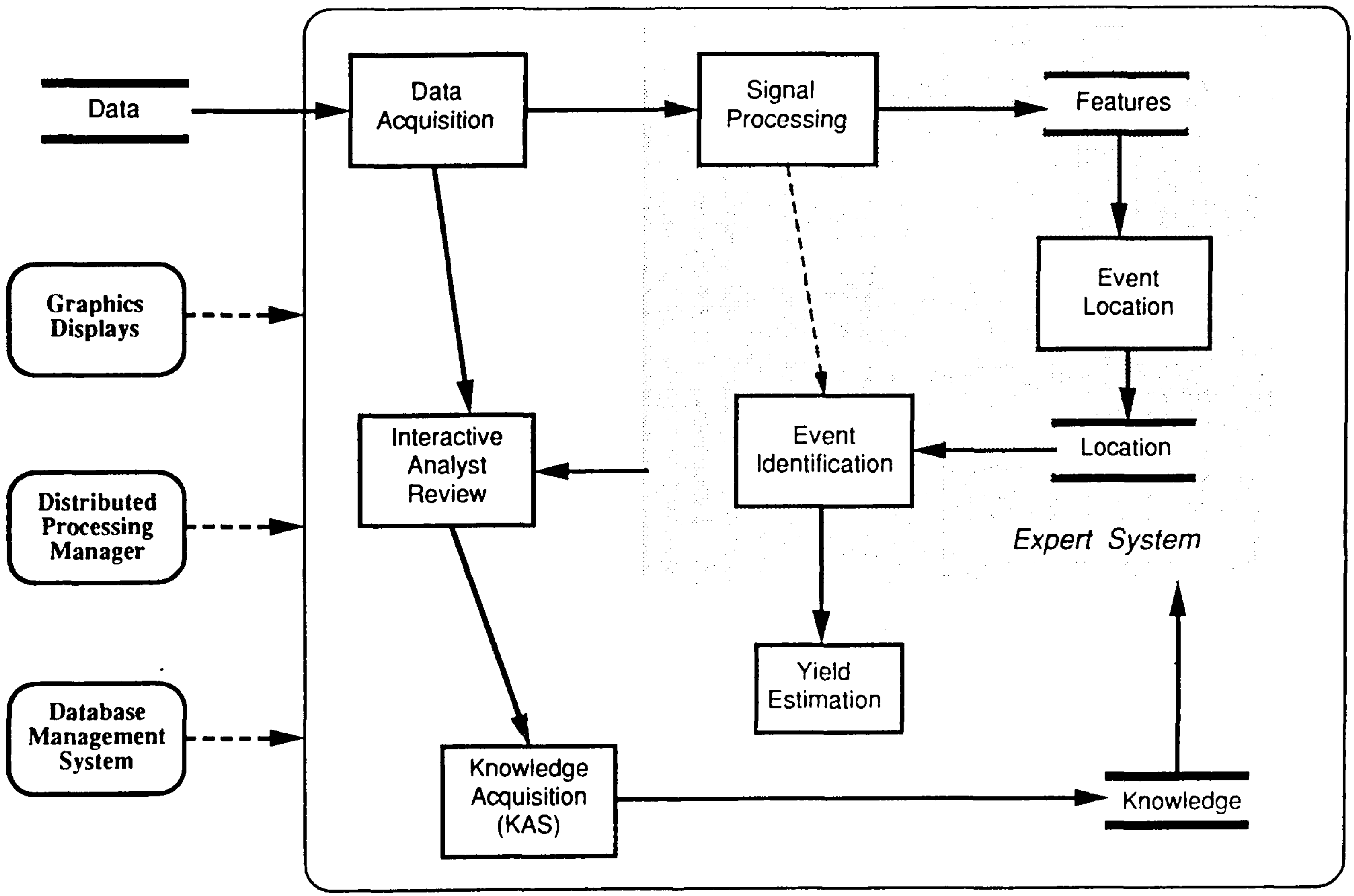


Figure 2.1. The major functional elements and data objects in *IAS* are shown with solid arrows indicating the dominant direction of dataflow. The key software facilities used to integrate the system are also shown at the left.

detected signals and their *features* to locate events.

<u>*Location* (data object)</u>
The output of the *Event Location* element is the location (including confidence limits), details about the signals used to form this location, and details about the reasoning leading to this solution.

<u>*Event Identification* (functional element)</u>
Given a located event, the "expert system" identifies it as an earthquake, mining explosion, nuclear explosion, or some other type of seismic event. The basis for this identification and an estimate of confidence in its validity is part of the "identification." The dotted arrow inside the "expert system" in the figure indicates that additional signal processing is often done during the *Event Identification.*

<u>*Yield Estimation* (functional element)</u>
For explosions there is a process external to the "expert system" which estimates the yield. The *IAS* computes seismic magnitude and other event attributes that are used for yield estimation. S-Cubed is developing a comprehensive yield estimation methodology under a separate project.

<u>*Interactive Analyst Review* (functional element)</u>
The solutions determined by the "expert system" are reviewed here by a human analyst who validates them, making corrections as necessary. This provides quality control for publication of the solutions obtained by the system. It also provides a fundamental element of the *IAS* concept for *knowledge acquisition.*

<u>*Knowledge Acquisition* (functional element)</u>
This module analyzes results from the automated processing and corrections made by the analyst to develop new *knowledge* to improve the performance of the automated processing. The design concept is described in Section 2.4.

<u>*Knowledge* (data object)</u>
With the aid of the *knowledge acquisition* module, new *knowledge* is acquired in the form of the rules and scripts used by the system.

<u>*Graphics Displays* (software facility)</u>
These displays provide the man-machine interface for operating and maintaining the system, as well as for reviewing the results it produces. All the graphics is done with X-Windows. The most important displays emphasize maps and waveforms to summarize and manipulate results produced by the system. Also, abstract graphical presentations of the system hardware and software architecture simplify operations and maintenance.

<u>*Distributed Processing Manager* (software facility)</u>
As will be seen in Section III, the *IAS* software architecture divides the system into nearly independent processes that communicate with inter-process communication (IPC) messages. A *Manager* process is used to manage and monitor these IPC messages. This process also provides facilities for system administration (startup, process migration, etc.)

<u>*Database Management System* (software facility)</u>
The seismic waveform segments are bulky data objects managed by the UNIX file system. Nearly all of the other data used by the system are parameters managed by a relational database management system (RDBMS) which is INGRES in the initial implementation. All

processes using parameter data write and read data directly to and from the RDBMS.

2.3. OVERALL ARCHITECTURE OF THE *IAS* EXPERT SYSTEM

The shaded area in Figure 2.1 shows the *IAS* "expert system." The distinguishing features of this portion of the overall system are:

- The input is the unprocessed seismic data.
- The output is the interpretation of the data, including events (location and identification), and detected seismic phases (associated with events and unassociated).
- The processing is done in a fully automated way, with no human intervention.

In this section we provide conceptual view of this architecture. More detail appears in Section 4.3.

The major steps in the automated analysis of the data are shown in Figure 2.2. The first step is *signal processing*. The full incoming data stream (the "time series") are input to this module which does the following operations:†

1. *Quality Control* - The individual channels are analyzed to detect spikes, dropouts, and noise bursts. Faulty time segments are repaired when possible, but are usually deleted from further processing.
2. *Beamforming* - A fixed suite of filtered beams are computed.
3. *Signal Detection* - The short-term (STA) and long-term (LTA) average amplitude is computed for each beam, and detections are declared when the STA/LTA exceeds the detection threshold for that beam. When more than one beam threshold is exceeded, simple rules are applied to select one as the "detecting beam."
4. *Onset-time refinement* - Segments containing detections are analyzed to refine the onset time estimate, with details of the analysis depending on which beam is the "detecting beam."
5. *Amplitude and period estimation* - The amplitude and period of detections are computed using preset criteria which vary with detecting beam.
6. *Spectrum calculation* - The spectrum of the signal and a previous "noise" segment are calculated according to rules for the window selection.
7. *Polarization analysis* - The available three-component data are subjected to polarization analysis and the results are summarized with a small number of parameters.
8. *f-k calculation* - The frequency-wavenumber calculation is done for a several-second segment of data around the detection and a band of frequencies around the dominant frequency of the detection.
9. *Azimuth and slowness estimation* - The f-k power contours are analyzed to estimate the azimuth and slowness and the error in those estimates.

The *signal processing* module was written in Fortran during the *IAS* project. However, many of the functional subroutines were adopted intact or adapted from NORSAR programs (see Section 4.2). The output of the *signal processing* module includes detected signals and

† These operations are described in general terms here, focusing on fixed aspects of the architecture. More specific design information is provided in Section 4.2, but we note that the details may change as the system evolves and improves.

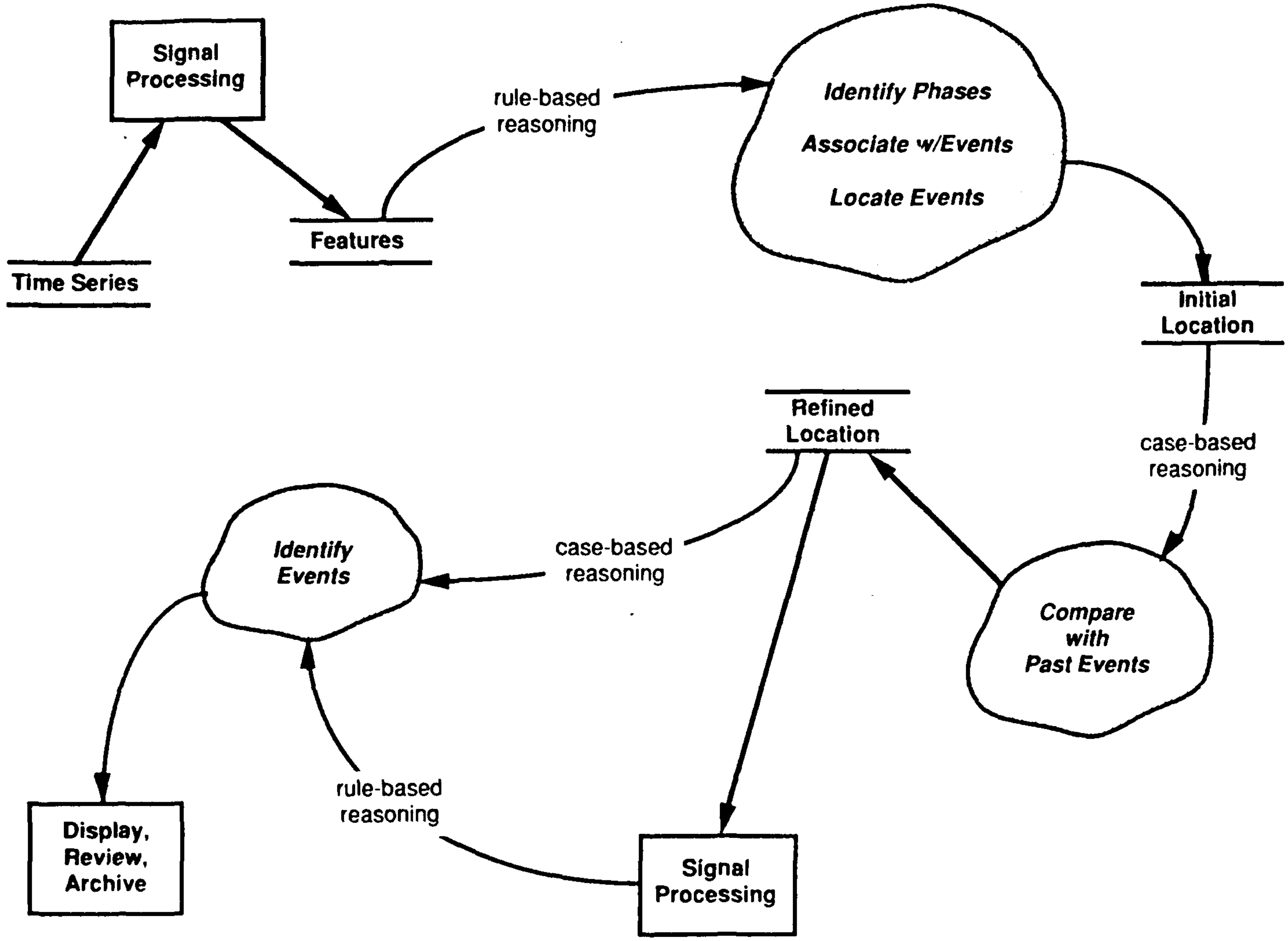


Figure 2.2. A conceptual view of the *IAS* expert system for automated location and identification of seismic events.

parameters describing the character of these signals. These are called "features" and are used to locate events.

As shown in Figure 2.2, "rule-based reasoning" is applied to the "features" to identify the phases, associate them with events, and compute an initial location for each event. The general organization of this portion of the "expert system" is shown in Figure 2.3. The data from each array are first processed separately to obtain "single array locations," and the three major steps in that processing are shown. First, each signal detection is classified into one of four phase-types, regional P, regional S, teleseism, and noise. This is primarily based on the slowness estimate, though other information (e.g., dominant frequency) can be introduced into the rules when it is helpful. The next step is to collect the phases into groups that appear to be from the same event. A number of rules are used to do this, but the most important look for a sequence of phases (with P before S) with azimuths that overlap (within the error bounds). The initial hypothesis is that all phases with overlapping azimuths within an appropriate time window are from a single event. Additional rules are then used to separate the sequence into groups of phases from multiple events when contradictions to the single-event hypothesis are encountered.

The next step in the single array processing is to associate and identify individual phases in the event groups. That is, particular phases are identified as Pn, Pg, Sn, Lg, Rg, or remain as P or S. Any two regional phases are adequate to compute a location (using the technique of Bratt and Bache, 1988) when each phase has an onset time and azimuth.

Single array locations generally have large error bounds, which is easily seen by noting that n° error in azimuth translates to 17.5n km error in location at a range of 1000 km, even if the range is estimated perfectly. If a phase is misidentified (e.g., Sn is mistaken for Lg), the location will be grossly inaccurate. Thus, association with even a single measurement from another station or array provides a major improvement in the location accuracy. For this reason "network processing" is emphasized, as is reflected in Figure 2.3.

The "network processing" is conceptually similar to the automatic association procedures used to analyze teleseismic data (e.g., Engdahl and Gunst, 1966; Slunga, 1980). The "single array locations" provide initial location hypotheses. The system first seeks corroboration of the single array location from one array with locations and individual phases at the second. When no corroboration is found, the system backtracks to revise the single array locations (including the phase identifications and associations), then tries again to find corroboration. The backtracking capability is indicated in the figure with grey two-headed arrows. During this process, hypothesized solutions can also be checked for consistency with other seismological knowledge (e.g., amplitude consistency).

The result of the "network processing" is an "initial location" based on general seismological knowledge and some of the region-specific knowledge needed to associate and identify phases (e.g., Lg does not propagate across oceanic paths, Pg is generally the largest amplitude phase at close ranges, etc.). Referring back to Figure 2.2, refinement of the location using knowledge gained from past events in the vicinity is the next step, which involves "case-based reasoning."

In "case-based reasoning" we use knowledge gained by a statistical synthesis of features from a past events (cases) in a particular area. Generally, the events are in a small area; often the are repeated explosions in a single mine. There are three somewhat different ways thi knowledge can be applied:

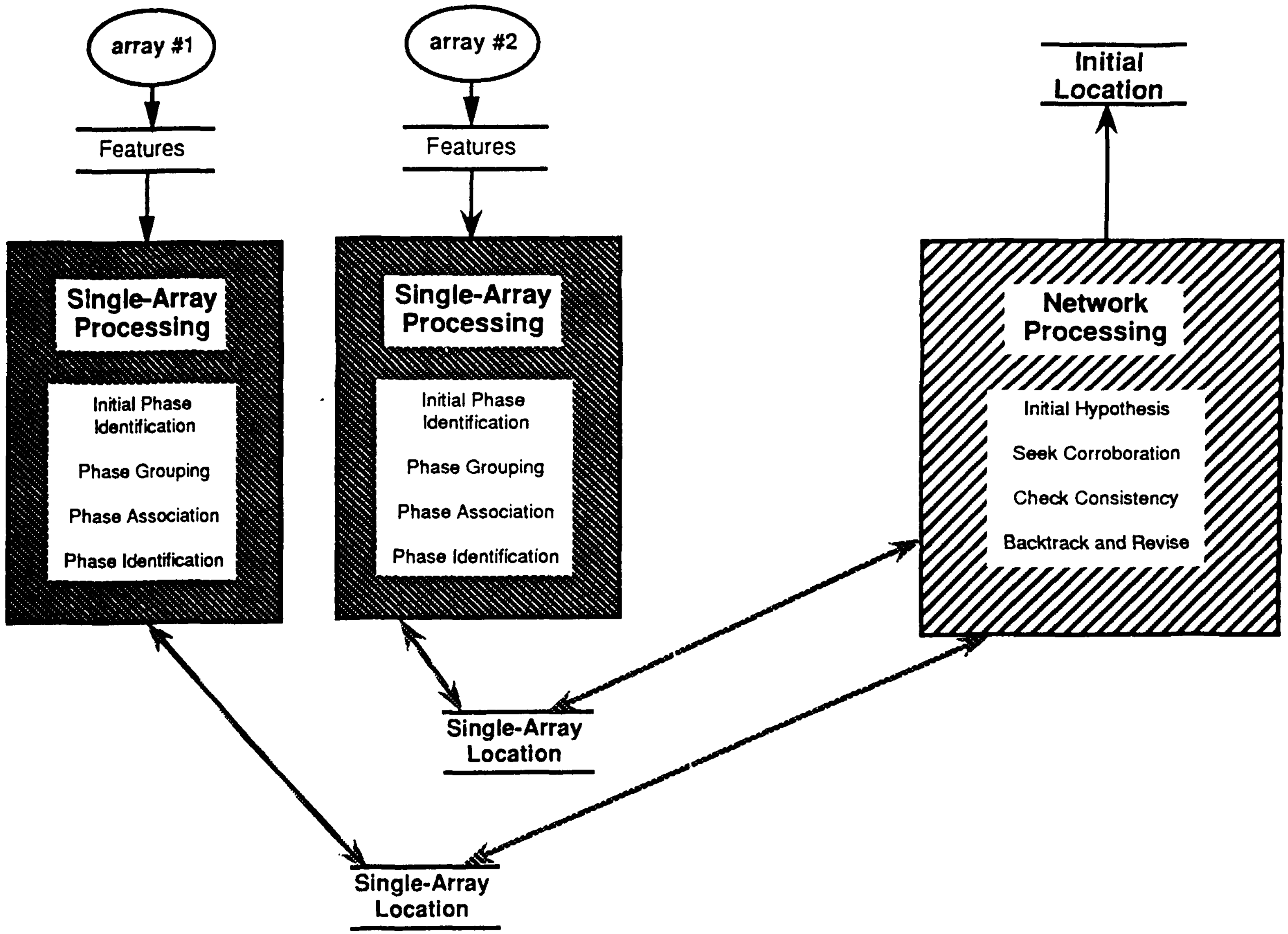


Figure 2.3. The rule-based reasoning from "features" to an "initial location" shown in Figure 2.2 is expanded to indicate the major steps in the reasoning process.

- The location is refined by recomputing it relative to the location of past events. This is an implementation of "master event" methods (e.g., Douglas, 1967; Jordan and Sverdrup, 1981) within the context of this system.
- The features from the "initial location" (apart from travel-time and gross amplitude consistency which are considered at an earlier stage) can be so different from those expected in the area that the "initial location" is rejected (i.e., backtracking is initiated to find a better solution).†
- An event is seen to be so similar to a particular class of past events (e.g., events in a mine) that it can be said with confidence to be another instance of that class. For mines that are independently located (e.g., by overhead photography) this provides a location more accurate than is possible with travel-time and azimuth data from a few arrays. It also provides powerful evidence for identifying the event.

Implementation of "case-based reasoning" for the latter two involves pattern matching. The specific pattern recognition scheme applied in *IAS* is described in Section 4.2. The basic concept is to select a set of parameters characterizing events in the region of interest. The mean value and its variance are determined statistically. New events are compared to this pattern of parameters (called a "script" in *IAS*) and the closeness-of-fit is calculated. Rules are used to develop conclusions from the closeness-of-fit metric. The method is sensitive to the selection of parameters included in the script, the weighting of these parameters, the events ("cases") used to compute the script, the closeness-of-fit metric, and the rules used to interpret this metric. Thus, much experience and many cases must be accumulated to make effective use of this method for the latter two applications of "case-based reasoning."

After applying this area-specific knowledge, we have a "refined location." The next step (Figure 2.2) is to identify the event. Of course, the crucial objective is to identify underground nuclear explosions, but these are rare in the region covered by the NORESS and ARCESS arrays. Also, the basic approach to event identification is to isolate for closer scrutiny a small number of "unidentified" events which might be nuclear explosions by positively identifying as many events as possible.† So the dominant technical problem for *IAS* is to identify earthquakes and industrial explosions occuring within the zone of regional coverage of the two arrays. In this zone industrial explosions are much more common, especially in that portion that lies within the Soviet Union.

As indicated in Figure 2.2, event identification involves both rule-based and case-based reasoning. The latter was described above. For example, we identify (with a measure of confidence) an event as a mine explosion because its signals are like those from previous explosions in that mine. The problem is to separate signal characteristics indicative of explosions in the mine from those that merely indicate an event in the vicinity of the mine.

The simplest application of rule-based reasoning for event identification is to identify the event based on its location. As one example, depth identifies earthquakes. Also, location is often the best indication that an event is not a nuclear explosion (e.g., it is in the Baltic Sea). For events not identified by location or similarity to previous events, the identification must be based on other characteristics of the seismic signals. As shown in Figure 2.2, this often requires more signal processing. For example, we compute the cepstrum and analyze it for peculiar characteristics of mining explosions (e.g., Baumgardt and Ziegler, 1988). Numerous

† Technically, it is much easier to say with certainty that an event is not a nuclear explosion than the converse. For example, we know an event deeper than a few kilometers is not a nuclear explosion.

other techniques have been suggested involving spectral ratios, phase amplitude ratios, etc., and the particular set implemented in *IAS* is described in Section 4.5. Combining the evidence from these techniques is a straightforward application of rule-based reasoning. Since this is a difficult and unsolved problem, the details of the implementation are expected to change as experience accumulates.

The final stage shown in Figure 2.2 is to "Display, Review, Archive" the results. These functions are external to the "expert system" and are described in a different way in Figure 2.1. Conceptually, the most important external function is the *knowledge acquisition* described in the next section.

2.4. KNOWLEDGE ACQUISITION

The operational concept for *IAS* includes review and validation of all automated solutions by a skilled human analyst, and the *IAS* includes extensive capabilities for rapid and accurate analyst review. The significance for quality assurance is obvious, but *interactive analyst review* also provides the baseline needed for the acquisition of new knowledge to improve the expert system performance. The *IAS* concept for *knowledge acquisition* is expressed in a module called the "knowledge acquisition station" or KAS (Figure 2.1). The functions of the KAS include:

- *Explanation* - Explain the decision process leading to each solution developed by the expert system.
- *Performance Validation* - Compare the performance of the expert system with "correct" solutions obtained by a human analyst and annotate them accordingly.
- *Performance Analysis* - Provide statistics and other summary information to identify deficient elements of the knowledge base and select representative examples using those knowledge base elements.
- *Knowledge-Base Augmentation* - Add new knowledge to the knowledge base.
- *Knowledge-Base Validation* - Conduct tests to ensure that the augmented knowledge base leads to improved performance by the expert system.

The requirements for these functions are a major reason that expert systems technology is being used in *IAS*. We emphasize that there are some important features of this problem which require an unconventional (compared with most "expert systems") approach which integrates elements of our expert system with a relational database management system (RDBMS). Most expert systems provide *explanation*, and this can be as elaborate as needed while the relevant data remain resident in the expert system memory structures. However, in *IAS* most requests for *explanation* are expected to occur long after the processing is completed. More important, most useful seismological knowledge requires recognition of patterns in many events rather than details about a few particular events. Thus, *performance analysis* requires a synthesis of experience accumulated over time.

The *IAS* concept for *knowledge acquisition* is sketched in Figure 2.4. The key innovation in this concept is the caching of "audit records" in tables in the relational database management system ("database"). These "audit records" are written by the "expert system" to describe the decision process and identify the specific rules that led to key decisions. The full panoply of relational database search and retrieval tools can then be used to organize and synthesize the information in the audit trail and other tables describing the event. The major disadvantage of this approach is that the audit trail is incomplete, since not all decisions can be represented

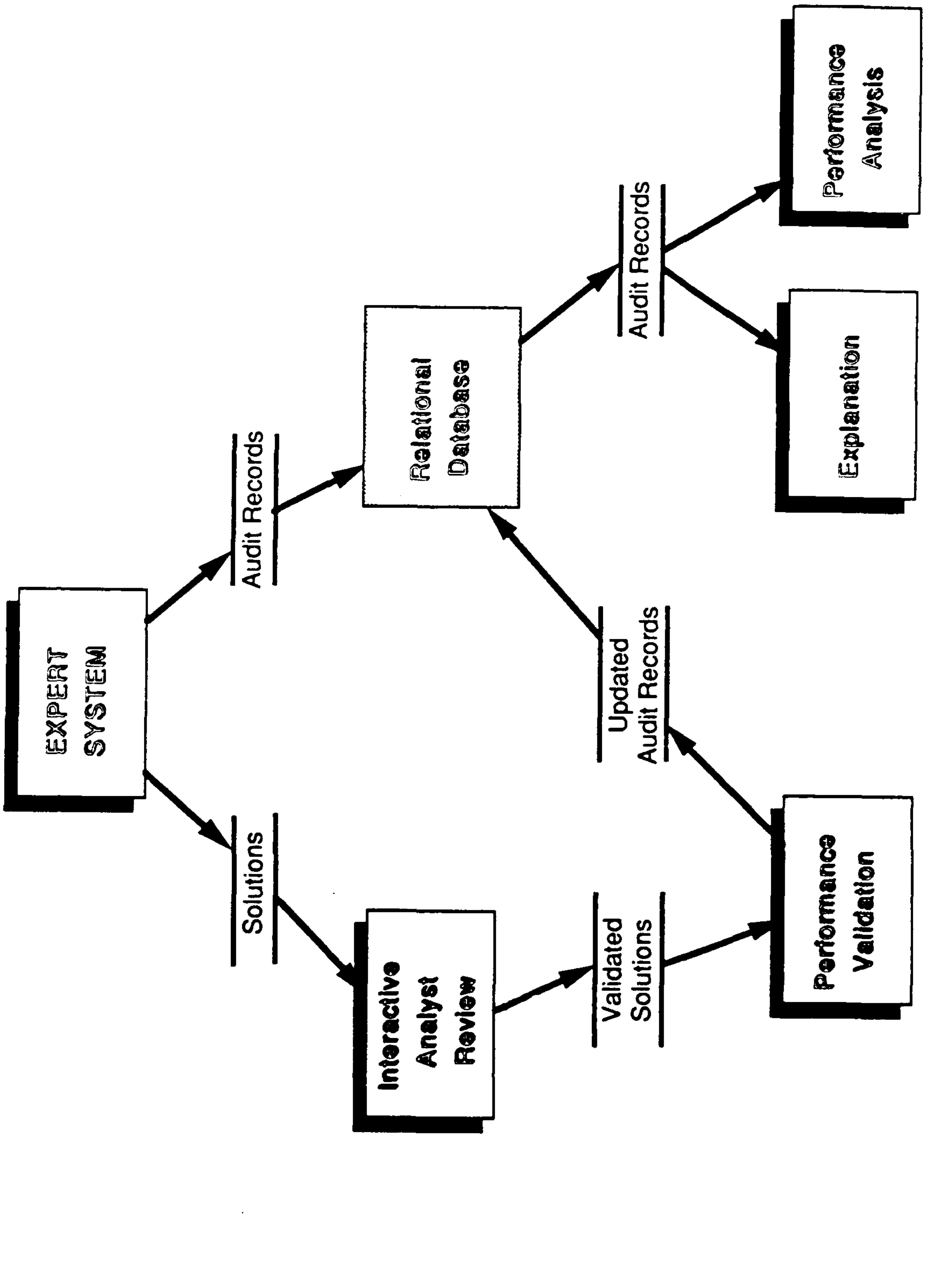


Figure 2.4. The *IAS* concept for *knowledge acquisition.*

within a relational database framework. In cases where more information is needed, the data can be reprocessed by the expert system to obtain a complete explanation.

As indicated in Figure 2.4, all "expert system" solutions are reviewed by a human analyst who validates correct solutions and corrects invalid solutions using a suite of interactive tools provided for this purpose. Linked with the *interactive analyst review* module is the *performance validation* module, which is itself an expert system. When the analyst validates or corrects a solution, a message describing that action is passed to the *performance validation* module. This module uses rule-based reasoning to identify those elements of the decision process that have been validated or implicitly invalidated by a correction. The corresponding audit records are updated with this information.

The *performance analysis* module includes database sorting and manipulation tools to organize and analyze the information about the performance of the expert system. For example, the seismologist can list each rule that has been invalidated more than x% of the times it was used. He can then identify all events that used this rule as part of the decision process, plot the event locations on a map to see the spatial distribution of events for which the rule was valid and invalid, retrieve the original data for selected examples, review the explanation, etc.

The KAS objective is to focus attention on deficient elements of the knowledge base and to facilitate a systematic review of relevant events to understand these deficiencies. Automated acquisition of knowledge (machine learning) from this information is not attempted. Instead, the concept is to provide the information in a convenient form to a highly-trained seismologist who will use his judgement to construct new knowledge to be added to the system. Since accumulation of adequate experience takes time, we anticipate that the knowledge base will be changed infrequently (perhaps once a quarter).

The remaining functions of the KAS are *knowledge-base augmentation* and *knowledge-base validation*. The first requires editing tools to change the knowledge base, and the second requires tools to verify that the new knowledge is consistent and results in improved system performance. In *IAS* the *augmentation* of the rules is done by editing the Lisp code expressing them. There is a separate *script acquisition system* which is used to construct new scripts (see Section 4.4). The concept for *knowledge-base validation* is to carry out regression tests using previously processed events. The "audit records" play an essential role in the selection of the events to be used for the regression testing since they include a record of each use of a particular element of the knowledge base.

In summary, when viewed from a "knowledge-based system" perspective, the important features of *IAS* are:

- The requirement for unattended automatic interpretation of incoming data.
- The availability of a human expert capable of validating the solutions obtained from the automated system.
- The requirement for caching a record of the decision process for retrieval long after the automatic solution is completed.
- A complex problem domain that makes automatic knowledge acquisition (machine learning) so difficult as to be impractical for now.

The decision process and knowledge base have been structured to allow caching of the needed information within the confines of a relational database. This requires tradeoffs, but it does not appear to have imposed any significant limitations on the architecture of the *expert system* for the automated processing.

2.5. *IAS* ARCHITECTURE

A high-level sketch of the *IAS* architecture was presented in Figure 1.3 and described in Section 1.3. In Figure 2.5 and this section we expand the description of the architecture to the next level of detail. As shown in the figure, the real-time NORESS data are transmitted via land-line to the NORSAR Data Analysis Center (NDAC). The real-time ARCESS data are transmitted in a similar way via satellite link. As the data are acquired, quality control and state-of-health checks are applied. The full data stream from each array is stored on a "disk loop" which is a first-in, first-out data buffer which contains the most recent 84 hours of seismic data. At the same time, all data are archived on tape in the *continuous data archive* shown in the figure. All these elements are external to the *IAS* system which begins by retrieving data from the "disk loops" for each array.

The *IAS* includes the software to retrieve the data from the disk loops, the *signal processing* shown in Figure 2.5, and the elements connected to NORSAR by the "Unix Wide-Area Network Connection." Thus, the *IAS* includes computers and software on three Local-Area Networks" connected by the "Unix WAN." The two LANs on the right are the *Automatic and Interactive Analysis* modules described in Sections 2.2-2.4 and the *Central Data Repository* (CDR). The results obtained by the *IAS* analysis (event interpretations and waveform segments) eventually migrate to the CDR for long-term storage and retrieval by other users of the data. The latter two WANs are colocated at the Center for Seismic Studies, while the NDAC connection requires a satellite link. Using computers anywhere on this WAN is little different from sitting at the computer console, though the limited bandwidth (56kbps) and travel-time delay (about 0.5 sec to echo) make it inconvenient to do some kinds of work over the satellite link.

The processing is distributed to keep the data-intensive *signal processing* near the real-time data acquisition at NDAC because only a portion of the data (10-20%) include signals of interest. As shown in Figure 2.5, the full-period data remain at the NDAC, and only "event segments" are transmitted to the Center for Seismic Studies for eventual archiving in the CDR. These "event segments" are requested automatically by the "expert system" using simple rules for the selection of segments. These rules consider the type of event (local, regional or teleseismic), and the duration needed to include all the signal energy and an appropriate pre-event noise sample. The particular rules (see Section 4.3) are easy to change with experience and changing requirements.

The "event segments" are queued for the *interactive analyst review* discussed in Sections 2.2-2.4. If the "expert system" makes an error, the analyst can request additional data which are available immediately if the request is made while the data are still resident on the 84-hour "disk loop."

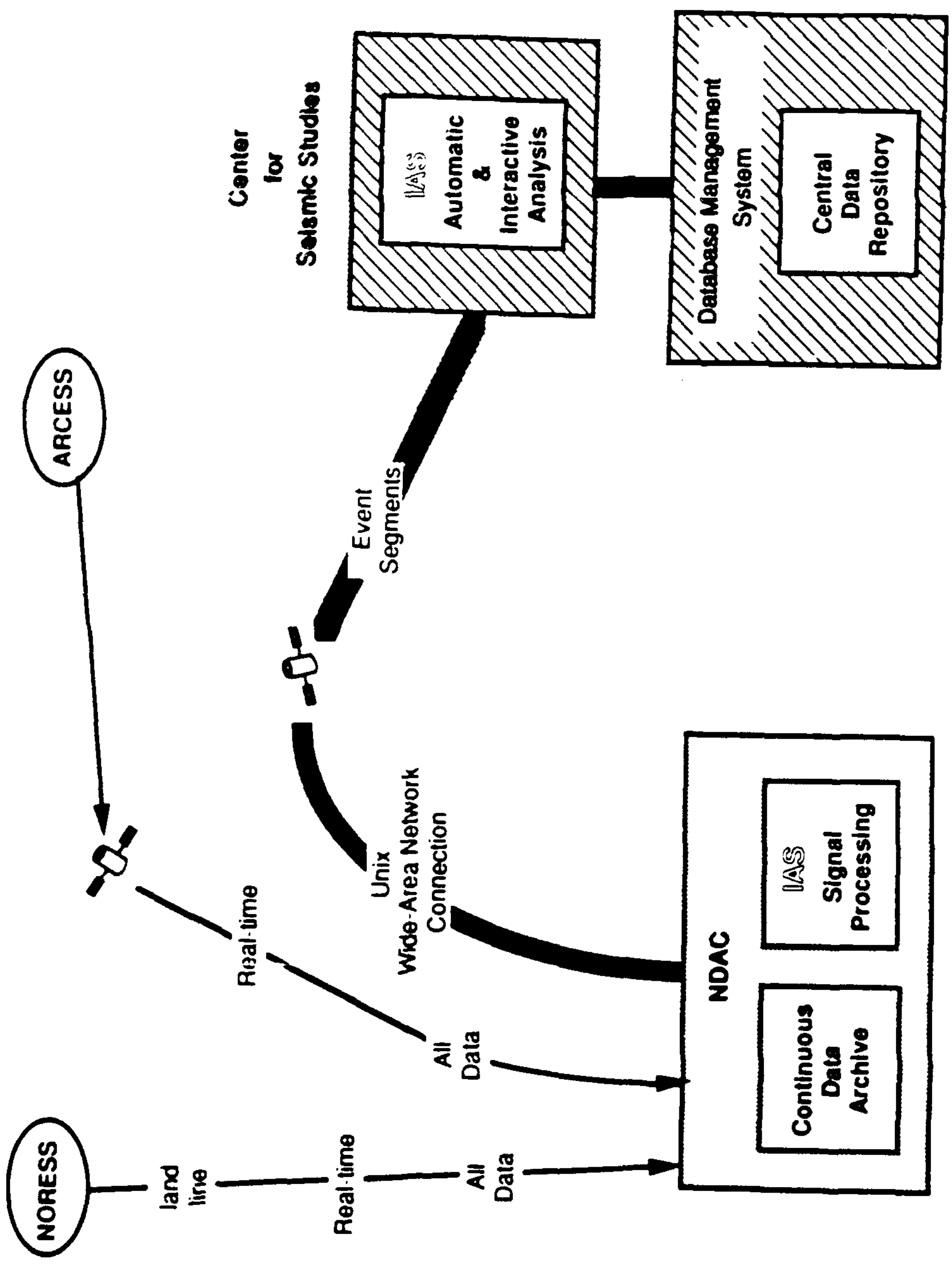


Figure 2.5. The overall architecture of *IAS*.

III SOFTWARE ARCHITECTURE

The overall concept for the system was described in general terms in Section II. In this section we describe how this concept is translated into software. In particular, we describe the overall architecture in terms of the individual processes and their interaction. In Section IV we describe in some detail how the functions are accomplished within each of the major modules. In Section V we discuss the mapping of these software modules to computer hardware.

3.1. *IAS* SOFTWARE ARCHITECTURE

A high-level view of the software architecture is provided in Figure 3.1. The system includes 43 processes plus the relational DBMS. Thirty-seven of these processes are shown in Figure 3.1 grouped into classes with closely related functionality. The other 6 processes provide control and administrative functions, and no attempt is made to display them graphically here.

In subsequent sections we will describe each of the processes included in the *IAS* system. From a seismological perspective the major processes are SigPro, ASSESS, EventId, ScriptMatch, MERSY, Sratio, ARS, SAS, PerfV, and iastalk. In Section IV we will describe how each of these major processes performs its functions.

The "arrays" and "Disk Loop" shown in Figure 3.1 are external to the *IAS* system. The "Disk Loop" is a first-in, first-out data buffer developed by Science Horizons, Inc. (SHI) and NORSAR. Each "Disk Loop" (one for each array) is configured to store 70 hours of data. SHI also provided the (*hub_cb2db*) program which became the *hub_cb2bg2z* process (described in the next section) after minor modification.

In the following sections we describe groups of related processes. The grouping is that shown in Figure 3.1, plus two additional groups not shown in the figure. With the exception of the first of these sections which describes the DBMS, all of these sections have the same form. Each begins with a brief description of the overall function of the processes in that group, and this is followed by a description of these processes in the following format:

Function The major functions performed by the process are described.

Language The language or languages (Fortran, C, Lisp, SQL) used in this process are described.

Input The input to the process is described from a functional perspective.

Output The output to the process is described at the same level of detail as the input.

IPC Processes communicating with this process via "Inter-Process Communication" messages (see Section 3.13) are identified, and the general content of the messages is described.

Parents Processes that spawn this process are identified.

Children Processes spawned by this process are identified.

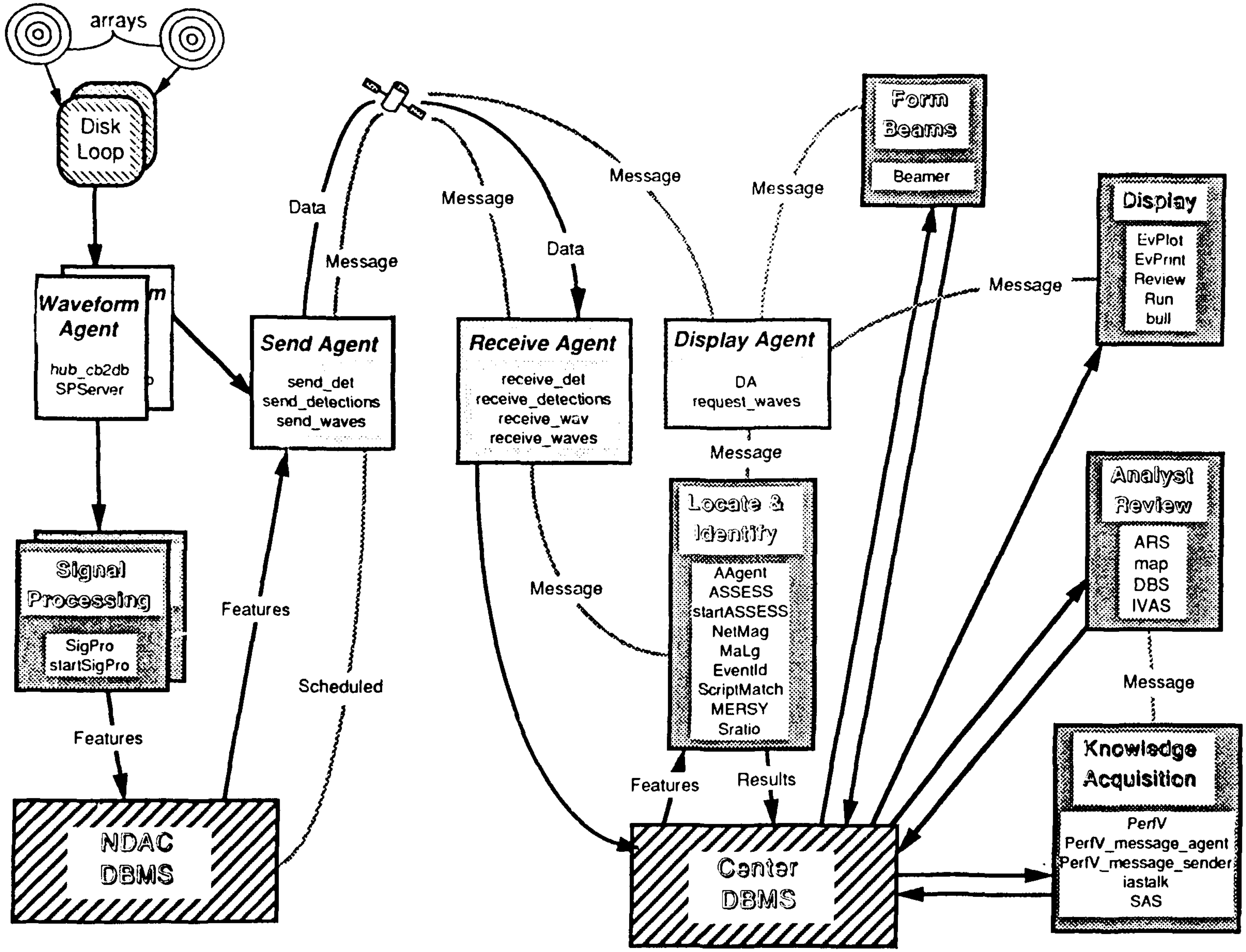


Figure 3.1. The software architecture of *IAS* is shown in terms of the major functional elements of the system. The processes within each of these functional elements are identified. The arrows indicate the flow of the most important data. The key messages exchanged during the automated processing are also shown.

3.2. NDAC DBMS AND CENTER DBMS

All parametric data generated by *IAS* are managed by a commercial relational database management system (RDBMS), and the processes retrieve and store data via SQL embedded in the source code. The initial implementation of the system used Ingres throughout. In November, 1989, the "NDAC DBMS" (Figure 3.1) was changed to Oracle. The database schema is an extension of the "Center for Seismic Studies Database Structure Version 2.8" (Brennan, 1987) with added attributes and tables required to manage new data objects introduced during the *IAS* development (see Appendix A). The concept motivating this DBMS schema is outlined in this section. Most of the new data objects were introduced to manage data generated by the expert system. There are also several new tables which provide process state information for fault recovery.

The database includes large data objects that are not stored in the RDBMS, but in the Unix file system. These are the time series data (stored in *w*) the spectra (stored in *fs*) and the f-k power spectra (stored in *fk*). Tables in the RDBMS (*wfdisc, fsdisc, fkdisc*) manage the pointers to these Unix files.

As shown in Figure 3.1, *IAS* includes independent DBMS's at NDAC and the Center. Data are transferred between the two using UUCP (see Sections 3.5 and 3.6). Independent counters are used at the two sites to provide the unique indexes. The files (*w*, etc.) are transferred in an analogous way, with independent *wfdisc*, etc., tables maintained in the two DBMS.

An abstract view of the *IAS* DBMS schema is presented in Figure 3.2. The major tables are the *detection, detloc, loc* triad that describe events, and the *audit* table that stores a history of the decision process. Each detected signal is represented by a tuple in the *detection* table, and each event is represented by one or more tuples in *loc*. The *detloc* table links events to detected signals associated with them. The many-to-one linkages from *detloc* indicate that many detections are associated with one event, and that a single detection may be associated with several (hypothesized) event solutions. This separation of detections from events with a linkage between them is a powerful concept introduced in the original Center DBMS (Berger *et al.*, 1984) where it appears in the *arrival, assoc, origin* triad. The triad in Figure 3.2 are these same tables adapted to the *IAS* regional array problem. As shown in the figure, many tables can be added (with one-to-one linkages) as the need arises to describe the signals and events.

New features introduced in the *IAS* RDBMS include the *audit* relations and the heirarchical linkage within the *detloc* and *loc* tables (represented by "ancestors" and "children"). In *detloc* this is used to link several interpretations of a particular detection (e.g., the automated processing identifies it as Sn, but the analyst changes it to Lg). In *loc* this is used to link an evolving series of hypotheses for the solution for a particular event.

The *audit* data are described in some detail in Sections 4.3.4 and 4.7.1. As indicated in the figure, many *audit* records are written (by *ASSESS*) to explain the reasoning for each association between a detected signal and an event solution. There are one-to-one linkages to tables that elaborate this reasoning, and many-to-one linkages to tables specifying the rules.

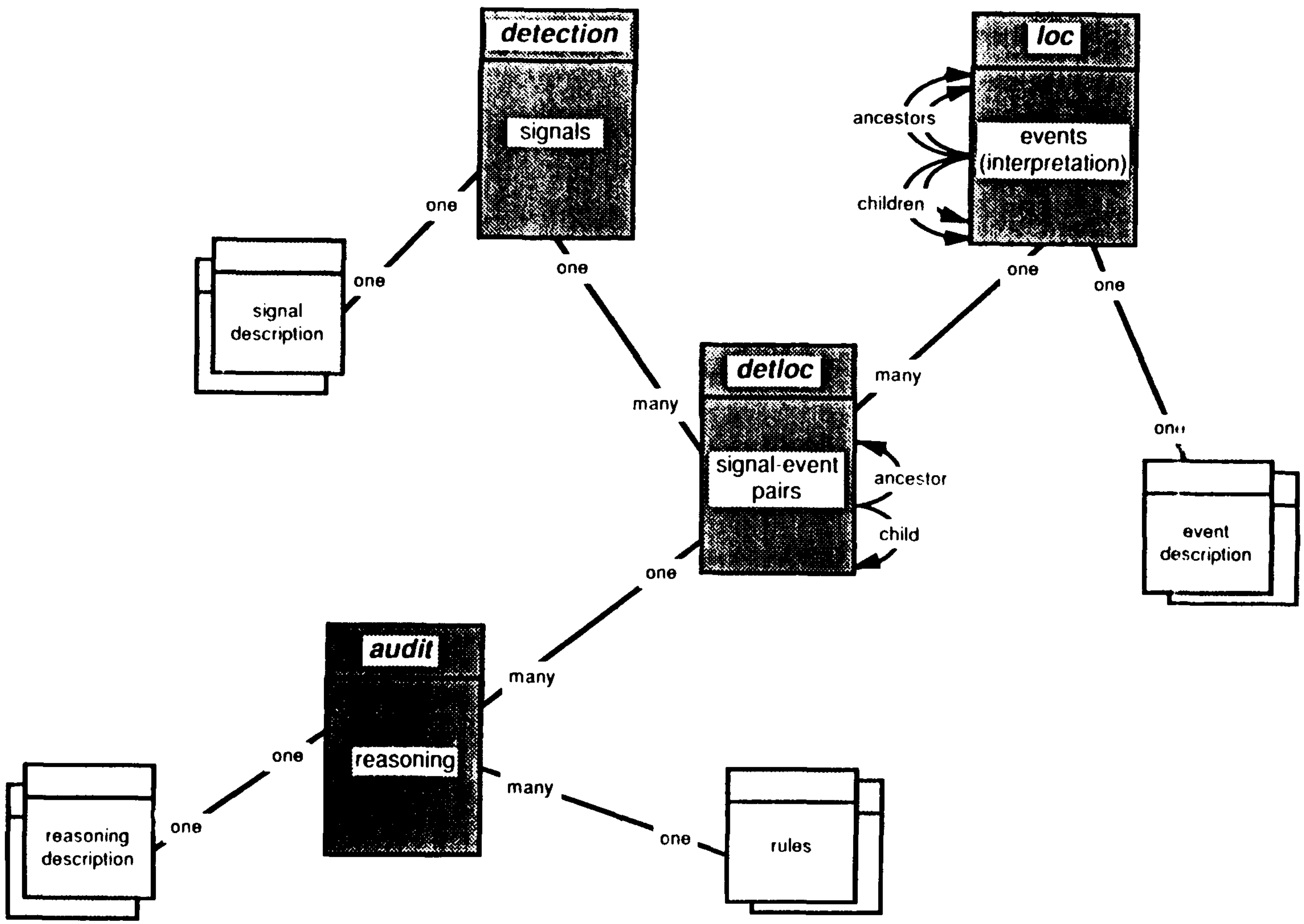


Figure 3.2. The fundamental organization of the tables in the *IAS* relational DBMS.

3.3. WAVEFORM AGENT

The basic function of these processes is to extract data from the "Disk Loop" for the elements of the system that need them. The *SPServer* process included in this element is intelligent process which controls much of the automated processing at the NDAC. The two processes included in the **Waveform Agent** are described below.

******hub_cb2dbg2z******

Function This process extracts a specified segment of data from the circular buffer and converts it to the *IAS* external file format (.wfdisc and .w) and inserts the .w files into the local file system.

Language C.

Input The start-time, end-time and channel identifiers for the data segment requested.

Output The .wfdisc and .w formatted version of the requested data.

IPC None.

Parents *SPServer, send_waves*

Children None

******SPServer******

Function This is an intelligent data server for *SigPro*. *SPServer* receives requests for new data from *SigPro*, frees disk space if necessary, then runs *hub_cb2dbg2z* to get the time series data. The length of the data segment retrieved depends upon the processing status of *SigPro*‡. *SPServer* also inserts the wfdisc information into the local DBMS.

Language C.

Input The .wfdisc file created by *hub_cb2dbg2z*.

Output The .wfdisc inserted into the local DBMS.

IPC Processing is initiated with a data request from *SigPro*. It sends a message to *SigPro* when new data are available for processing.

Parents *startSigPro*

Children *hub_cb2dbg2z*

‡ When *SigPro* is running faster than real-time, data are retrieved in 30 minute segments. The maximum segment extracted (when *SigPro* is behind real-time) is 2 hours. The segment length varies between these limits depending on the current situation.

3.4. SIGNAL PROCESSING

The overall function was described in Sections 2.2 and 2.3, and more detail will be provided in Section 4.2. Two processes are included.

******SigPro******

Function The signal processing described in Section 4.2 is done in this module. Knowledge of the last time processed is maintained in the DBMS, and this is used to request new data upon initiation by *startSigPro*. In continuing operation *SigPro* is controlled via conversational communication with *SPServer*.

Language Fortran with embedded SQL and some C subroutines for waveform data access.

Input Time series for the all short-period channels (25 vertical and 8 horizontal channels at 40 samples/sec for NORESS and ARCESS) are retrieved from the local file system. In addition to .wfdisc, SigPro also uses quasi-station tables from the DBMS for site geometry and beam and filter indexing. From external files, SigPro accesses beam recipes and filter coefficients.

Output The "features" are written to the local DBMS and file system. These include parameters describing signal detections and their character (see Section 4.2) inserted into the appropriate tables (primarily detection) in the DBMS, and files with the Fourier and f-k spectra for each detection.

IPC *SigPro* sends a message to *SPServer* when it completes its processing of a data segment. *SigPro* receives a message from *SPServer* when more data are available for processing.

Parents *startSigPro*

Children None.

******startSigPro******

Function This script starts all the processes needed for signal processing in Norway. It is provided as a convenience for the administrator of the system.

Language Bourne shell.

Input None.

Output None.

IPC None.

Parents None.

Children *Dispatcher, SigPro, SPServer, d_test.*

3.5. SEND AGENT

The basic function of the processes in this group is to transfer data from the NDAC to the Center. The UUCP protocol is used for the transfer, so these processes reformat the data for transmission via this method. The transmitted data fall into two categories which are handled differently. The data created by *SigPro* are transmitted on a regular schedule (e.g., hourly). Segments of unprocessed time-series data are transmitted upon request from the **Display Agent**, with the request based on interpretation of the data by the **Locate & Identify** group of processes. There are three processes in this group.

******send_det******

Function	This process extracts data describing all detections written to the local database since the last transmission, packages these data for transmission, and transmits them to the Center via uux. The data include parameters from the DBMS (primarily in detection) and files (spectra and f-k).
Language	C and SQL.
Input	The SigPro-time table from the DBMS
Output	The input data repackaged for transmission via uux.
IPC	None.
Parents	*send_detections*
Children	None.

******send_detections******

Function	This script provides run-time parameters for *send_det*. . It is initiated on a regular schedule (e.g., once per hour).
Language	Bourne shell.
Input	None.
Output	None.
IPC	None.
Parents	Spawned on a prescribed schedule by cron.
Children	*send_det*

******send_waves******

Function	This script accepts requests for specified segments of time-series data, retrieves the requested data via the *hub_cb2dbg2z* process, and sends them to the requested address via uux.
Language	Bourne shell.
Input	A description of the requested data in terms of station (array) name, start-time, and end-time.
Output	Time-series data formatted for transmission via uux.
IPC	None.
Parents	Spawned by request_waves via uux.
Children	*hub_cb2dbg2z*

3.6. RECEIVE AGENT

The function of the processes in this group is to receive the data transmitted via UUCP by the *Send Agent* group of processes and to insert them in the local file structure and DBMS. The data extracted from the NDAC DBMS are written to the corresponding tables in the local DBMS, and the data objects managed by the file system are written to the appropriate parts of the local file system.

******receive_det******

Function	This process receives the detection data transmitted via uux by send_det, unpacks them, and inserts them into the local DBMS and file system.
Language	C.
Input	The detection data formatted for transmission via uux.
Output	The detection data inserted into the local DBMS and file system.
IPC	Message to Agent informing it of newly arrived data.
Parents	*receive_detections*
Children	None.

******receive_detections******

Function	This script provides run-time parameters for *receive_det.*
Language	Bourne shell.
Input	None.
Output	None.
IPC	None.
Parents	Spawned by a uux process spawned by *send_det.*
Children	*receive_det*

******receive_wav******

Function	This process inserts the wfdisc tuples transmitted by *send_waves* into the local DBMS.
Language	C.
Input	Wfdisc tuples formatted for transmission via uux.
Output	Wfdisc tuples inserted into the local DBMS.
IPC	Message to *DA* informing it that new data are available for display.
Parents	*receive_waves*
Children	None.

****receive_waves****

Function This script receives the time-series transmitted by *send_waves*, formats them into the proper format (.w), and inserts these files into the local directory structure.

Language Bourne shell.

Input Data packaged by *send_waves*.

Output Files formatted according to *IAS* format.

IPC None.

Parents Spawned by a uux process spawned by *send_wav*.

Children *receive_wav*

3.7. LOCATE AND IDENTIFY

The processes in this group retrieve the features describing the detections from the local DBMS and file system and operate on these data to associate detections with events and then locate these events. Those detections that are associated with seismic events are processed to isolate features that identify their source as natural or man-made seismic events of specified type. The major process in this group is *ASSESS*, the expert system which associates the detections and locates events. Subsequent processes operate on those groups of detections associated with events by *ASSESS*.

****AAgent****

Function This process specifies the detections to be processed by *ASSESS*. It is initiated by a message from *receive_det* indicating that new detections are available, or by an operator command.

Language C. with SQL

Input The time window including the detections to be processed.

Output None.

IPC Messages from *receive_det* indicating that detections are available; messages to *ASSESS* identifying the detections to process.

Parents *Manager*.

Children None.

****startASSESS****

Function This script conveniently starts *ASSESS*.

Language Bourne shell.

Input None.

Output None

IPC None

Parents *Manager*.

Children *ASSESS*.

****ASSESS****

Function This process is the expert system that associates detections with seismic events.

Language Lisp and some Fortran and C subroutines with embedded SQL.

Input "Features" describing detections extracted from the appropriate tables in the DBMS.

Output "Results" including the associated detections, the event locations and an an audit trail describing the reasoning. The major DBMS tables include .loc, .detloc, and .audit.

IPC Messages from *AAgent*; messages to *DA*.

Parents *startASSESS*.

Children None.

****EventId****

Function This process controls several processes that compute data used for event identification and integrates the results to provide an identification.

Language C.

Input None

Output Event identification "Results" to the eventid table in the DBMS.

IPC Messages from *ASSESS*. Messages to event identification processes: *ScriptMatch*, *MERSY*, *Sratio*.

Parents *Manager*.

Children None.

****ScriptMatch****

Function This process attempts to match the "Features" of a group of detections associated with an event to the pattern (a "script") of detections from selected sets of previous events. A close match indicates that the event is similar to the events used to make the "script."

Language Lisp

Input "Features" and "Results" are retrieved from the appropriate tables in the DBMS. Scripts are computed by *SAS* and are stored in special files.

Output The results of the script-match are written to the DBMS.

IPC Messages from *EventId*.

Parents *Manager*.

Children None

****MERSY****

Function The Multiple Event Recognition System analyzes the spectra of the detections associated with an event to seek evidence that the event is made up of several explosions closely spaced in time. Such events are common in many types of mining, and strong evidence of this "ripple-firing" provides high confidence that the event is an industrial explosion. Particular patterns can sometimes be used to identify events in a specific mine.

Language C, Fortran and SQL

Input "Features" and spectra from the DBMS and filesystem.

Output Results of the analysis are written to the DBMS and filesystem.

IPC Messages from *EventId.*

Parents *Manager.*

Children None.

****Sratio****

Function The Sratio process analyzes the spectra of Pn and Lg detections associated with an event to obtain an estimate of the ratio of S-wave radiation to P-wave radiation. A high ratio is consistent with an earthquake; a low ratio is inconclusive.

Language Fortran.

Input "Features" and "Results" are retrieved from the appropriate tables in the DBMS, and the spectra are retrieved from the file system.

Output Results of the analysis are written to the DBMS.

IPC Messages from *EventId.*

Parents *Manager.*

Children None.

****NetMag****

Function A request for a magnitude is sent to this process which then directs the computation of the requested network magnitude by initiating the individual station magnitude calculations. In *Ias* all station magnitudes are computed by *MaLg*.

Language C.

Input None.

Output None

IPC Messages specifying the event for which the magnitude is to be computed are received from the requesting process (e.g., DbS, DA) and messages requesting a station magnitude are sent to *MaLg*.

Parents None.

Children None.

******MaLg******

function This process estimates the magnitude for a specified event from the amplitude of Lg. A recipe file specifies the channels (beams or single elements), time window, filter, and distance correction for the computation.

Lanuage Fortran.

Input The event location and quasi-static files providing the needed parameters (e.g., instrument corrections, recipe files) are obtained from the DBMS. Unprocessed or beamed waveforms (depending on the recipe) are obtained from the database.

Output The computed magnitudes are written to the DBMS; station magnitudes to .mag, and an updated aveerage network magnitude to .loc.

IPC Messages from *NetMag*

Parents None.

Children None.

3.8. FORM BEAMS

This process calculates beams for specified time segments and beam parameters retrieved from a beam recipe file. In routine (realtime) processing, several standard beams are calculated for each event. The beam recipe for these standard beams includes a coherent high-frequency (4-8 Hz) beam steered toward the event at an apparent velocity of 8.1 km/s, an infinite velocity low-frequency (1-4 Hz) incoherent beam, and an infinite velocity incoherent horizontal beam at (1-4 Hz). These beams were designed to emphasize Pn, Lg, and Sn, respectively.

******Beamer******

Function This process calculates a set of beams for a specified array elements, time window, azimuth, filter.

Language Fortran with some C subroutines for acquiring waveform data.

Input Raw waveforms (.w files) from the filesystem and the beam recipe specifying the beams to be calculated.

Output Beamed waveform data (.w) are written to the filesystem and the .wfdisc table is updated.

IPC Message from the *DA* specifying the event and time segment for which beams are to be calculated.

Parents *Manager*

Children None.

3.9. DISPLAY AGENT

The processes in this group retrieve from the NDAC the original time series for segments including the expected arrival time of detections from located events. They also initiate the display of the event solutions.

****DA****

Function The *DA* coordinates the various activities that are required once a solution has been formed, namely sending out the request for waveform segments, waiting for the arrival of the waveforms, initiating the beamforming and waiting for the completion of the beams, and plotting the results.

Language C.

Input The *DA* uses location solutions and travel-time tables to determine which waveform segments to request. For regional events, the selected segments begin 30 seconds before the expected Pn arrival time and have a 7 minute duration.

Output The *DA* has no output of its own; its products result from child processes. However, the *DA* does have an X status display.

IPC *ASSESS* informs the *DA* of new solutions. *receive_wav* informs the *DA* when requested waveform segments have arrived. The *DA* starts beamforming by sending a message to *Beamer; Beamer* responds when beamforming is complete. Finally, plotting of solutions is started by sending messages to *EvPlot* and *Review*.

Parents *Manager*

Children *request_waves*

****request_waves****

Function *request_waves* is a shell script for submitting requests for waveform segments from Norway. The script takes a station name and start and end times for the requested segment as parameters, then initiates a *send_waves* remotely in Norway via *uux*.

Language C shell.

Input The station name and start and end times of the requested segment.

Output None.

IPC None.

Parents *Display Agent*

Children *send_waves* is spawned remotely via *uux*

3.10. DISPLAY

This group of processes displays the results of *IAS* processing using X graphics on raster display devices and hardcopy on PostScript printers. The displays include text and graphics. The text displays include lists of detections with selected features and a seismic bulletin with locations and associated detections. The graphical displays include appropriately annotated waveform and map displays. Some processes display results automatically as they are created, others are initiated by an operator.

****EvPlot****

Function	This process formats a display of each event located by *ASSESS*. The display includes a map showing the event location and error ellipse with the associated detections (plotted as rays at the estimated azimuth). There are three standard beams for each array from *Beamer* All detections on each beam segment are marked as are the theoretical arrival times (for the estimated location) for major seismic phases. This process also lists selected features for each detection displayed.
Language	C with SQL
Input	"Features" and "Results" are retrieved from the appropriate tables in the DBMS, and the standard beams are retrieved from the appropriate .w files.
Output	A metafile description of the display.
IPC	Message from the *DA* to plot a designated solution.
Parents	*Manager*.
Children	*EvPrint*.

****EvPrint****

Function	The display formatted by *EvPlot* is plotted on a PostScript printer (hard copy) by this process.
Language	C.
Input	The metafile from *EvPlot*.
Output	Hardcopy output.
IPC	None.
Parents	*EvPlot*.
Children	None.

******Review******

Function	This process provides displays that are similar in format to those provided by *EvPlot*. However, the *Review* displays are done in X on a workstation. Also, *Review* does not use the embedded program that plots coastline maps for *EvPlot*, but sends messages to the X displays produced by *Map*.
Language	C with SQL.
Input	"Features" and "Results" are retrieved from the appropriate tables in the DBMS, and the standard beams are retrieved from the appropriate .w files.
Output	An X display showing waveforms and a table of detections associated with the specified solution.
IPC	Message from *DA* to plot a designated solution; message to *Map* to plot locations and detections.
Parents	*Manager*.
Children	None.

******Run******

Function	This process is used for demonstration. Its displays are nearly identical to those produced by *Review*. The only difference is that the waveform displays in *Run* scroll at a user-selected rate. Also, selection of the events to be displayed in *Run* is in terms of a time window rather than by an event identifier.
Language	C with SQL.
Input	"Features" and "Results" are retrieved from the appropriate tables in the DBMS, and the standard beams are retrieved from the appropriate .w files.
Output	An X display.
IPC	Message from operator specifying time period to display; message to *Map*.
Parents	*Manager*.
Children	None.

******bull******

Function	This process provides a bulletin summarizing the results obtained by *IAS*.
Language	C with SQL.
Input	"Features" and "Results" from the appropriate tables in the DBMS.
Output	A troff-formatted file to be printed on a PostScript printer.
IPC	None.
Parents	None.
Children	None.

3.11. ANALYST REVIEW

These processes provide the capability for interactive review and validation of solutions obtained by the automatic system. Four processes are included.

****ARS****

Function The Analyst Review Station is an interactive process providing a full suite of tools to review and correct solutions obtained by the *IAS* automated processing.

Language C with embedded SQL.

Input The particular event to be analyzed is selected by the analyst or via an *IPC* message. The results of the automated processing are retrieved from the appropriate tables in the DBMS and related files. Commands controlling the display and editing functions are input pointing and clicking with a mouse.

Output Corrected solutions obtained by the analyst are written to the appropriate tables in the DBMS. A link is maintained between the solution obtained by the automatic processing and that obtained by the analyst.

IPC Messages are sent to *Map* and *ivas* to plot locations and associated detections. After review of each event is completed, a message is sent to *PerfV* for performance validation. *ARS* can also receive messages specifying events to be displayed for analysis from *Map* and *DBS*.

Parents None.

Children None.

****Map****

Function This process provides a variety of interactive and automatic map manipulation and display functions. Numerous color maps are available in special files and can be selected interactively for display. These maps were produced from digital elevation and feature data obtained from NOAA and DMA. A variety of overlays showing cultural, geographical, political and seismological information can be selected interactively. Seismic locations and detections obtained by the automated processing or during analyst review are initiated by *IPC* messages which can be sent by automatic or interactive processes.

Language C.

Input Bitmaps and overlays are read from files which are located by information in *aesir_paths*. Interactive selection of displays is via pointing and clicking a mouse.

Output The graphics displays.

IPC Messages describing the locations and detections to be plotted are received from *ARS*, *Run*, and *Review*. Pointing and clicking on events plotted on the map sends to *ARS* the information necessary to retrieve from the DBMS all available information about that event.

Parents None.

Children None.

****ivas****

Function This is a special-purpose image processing and display system from International Imaging Systems. The major function is to process and analyze and manipulate satellite images, but it also displays and manipulates the digital maps displayed by *Map*. Many of the overlays available for *Map* can also be displayed on *ivas*. In particular, locations and detections obtained by *IAS* can be displayed on the images.

Language C.

Input Maps and satellite images are read from files. User control is mouse-driven.

Output Processed images are written to files for future display.

IPC Messages describing the locations and detections to be plotted are received from *ARS*, *Run*, and *Review*. Pointing and clicking on events plotted on the map sends to *ARS* the information necessary to retrieve from the DBMS all available information about that event.

Parents None.

Children None.

****DBS****

Function This Database Browser/Selector is an interactive process that is used to select events from the database for input to other processes.

Language C with SQL.

Input The user specifies ranges of parameters characterizing the locations desired *DBS* retrieves from the DBMS those events that satisfy the input constraints.

Output Results of the queries to the DBMS are displayed in tabular form. Pointing and clicking particular events selects them for transmission to another process.

IPC Messages identifying selected events can be sent to any application connected to the *Dispatcher* that accepts event identifiers.

Parents None.

Children None.

3.12. KNOWLEDGE ACQUISITION

The knowledge-acquisition processes are tasked with automating the correction, refinement and augmentation of the ASSESS knowledge-base. This is accomplished via two separate activities: "performance validation" and "performance analysis." Performance validation compares the solutions obtained by the automated processing (*ASSESS*, etc.) with the solution validated by the analyst (*ARS*, etc.). Based on this comparison it determines which elements of the automatic reasoning were correct and incorrect and marks the appropriate audit tables in the DBMS. Performance analysis refers to analysis of results of the processing, with emphasis on analysis of performance validation reflected in the audit records.

******PerfV******

Function This process compares the automated processing results with analyst results and marks the audit records appropriately.

Language Lisp.

Input The solutions from the automatic processing and analyst validation (primarily from the detection, detloc, loc tables and a series of tables with audit information).

Output Changes to the relations containing audit information.

IPC When the analyst completes review of an event, a message is sent to *PerfV* including a pointer to the tuples describing the automated solution and (when the solution is changed) the analyst solution.

Parents This process is initiated by a script (*startPerfV*) initiated by the *Manager* or an operator.

Children None.

******PerfV_message_agent******

Function This process is used when the operator prefers to defer *PerfV* processing. It intercepts the *PerfV* messages and caches them in a file.

Language C.

Input None.

Output A file containing the cached *PerfV* messages.

IPC The messages that are otherwise received by *PerfV*.

Parents This process is initiated by a script (*startPerfVagent*) initiated by the *Manager* or an operator.

Children None.

******PerfV_message_sender******

Function	This process emulates message transmission to *PerfV* from *ARS* using the messages cached in a file by *PerfV_message_agent.*
Language	C.
Input	A pointer to the file created by *PerfV_message_agent.*
Output	None.
IPC	Messages to *PerfV.*
Parents	This process is initiated by a script (*startPerfVmessages*) initiated by the *Manager* or an operator.
Children	None.

******iastalk******

Function	This process provides a natural-language interface to the relations containing the results of the processing and audit trail. The primary use is as a user-interface for performance analysis.
Language	NLI connection file.
Input	Processing results are obtained from the DBMS when requested by queries typed in English by an operator.
Output	None.
IPC	Messages to the *map* are created by an ephemeral process (*swan_agent*) initiated by a command to plot selected events.
Parents	None.
Children	None.

******SAS******

Function	SAS (Script Acquisition System) generates scripts from selected data contained within the database for use by the script matcher in the expert system.
Language	Lisp.
Input	SAS uses an set of origins provided by the user and queries the database for the seismic parameters associated with those origins. The end user may edit any of the parameter summaries contained within the script created by SAS.
Output	Scripts are saved in files in a directory specified in aesir_paths.
IPC	None.
Parents	None.
Children	None.

3.13. DISTRIBUTED PROCESSING MANAGEMENT

The distributed-processing management processes provide inter-process communication (IPC) and process coordination for the IAS distributed system. The Dispatcher is the IPC facility; the Manager is the process coordinator. Utilities are provided for handling logical pathnames and testing.

******Dispatcher******

Function	This process provides IPC communication facilities for the IAS system. Each IAS process connects to the Dispatcher which then routes messages between processes.
Language	C.
Input	None.
Output	None.
IPC	Besides handling the IPC communications for all the IAS processes, the Dispatcher accommodates special messages for initializing service, message monitoring and process coordination.
Parents	None.
Children	None.

******Manager******

Function	This process initializes/terminates, monitors and coordinates the *IAS* distributed system. The *Manager* is the main interface to *IAS* for the system administrator. It includes a graphics user-interface for process and message traffic monitoring and for system configuration.
Language	Lisp.
Input	Initialization files describing the system configuration.
Output	Graphics displays.
IPC	The *Manager* uses special *Dispatcher* messages to monitor and coordinate processing. It also determines the recipient of messages sent to a process class.
Parents	None.
Children	Many *IAS* processes are started by this process.

******aesir_paths******

Function	This script maps logical pathnames into physical pathnames, thus localizing pathname dependencies. All absolute pathnames in the IAS system should be referenced indirectly through this script.
Language	Bourne shell.
Input	Logical pathname.
Output	Physical pathname.
IPC	None.
Parents	None.
Children	None.

******d_test******

Function	This process is a generic process used to simulate the presence of any *IAS* process for testing. d_test connects to the *Dispatcher*, and allows the user to send and receive messages interactively.
Language	C.
Input	A process class name.
Output	None.
IPC	Responds to messages which apply to the process class being imitated.
Parents	None.
Children	None.

3.14. MISCELLANEOUS PROCESSES

The processes in this group are essentially utilities or administrative tools.

******mimic******

Function	This process is used to manage the evolving *IAS* software. It creates a new directory tree which is a replicate of the current directory tree. New versions of the software are then installed in this new directory tree.
Language	C.
Input	None.
Output	None.
IPC	None.
Parents	Called by an administrator of the system.
Children	None.

******TTTab******

Function	This process computes travel-time tables for a velocity model of the earth.
Language	Fortran.
Input	File with the velocity model; user specified phase id's, ranges and source depths.
Output	Files with travel-time tables for each specified phase.
IPC	None.
Parents	None.
Children	None.

3.15. LINES OF CODE IN *IAS*

The size and complexity of the code in these 43 processes is difficult to convey in a simple way. To give some concept for the scope of the software, some simple numerical measures are summarized in the table below. The code is divided into four classes: executable source code (in Fortran, C, and Lisp), libraries (in C), include files (containing C structure definitions), and shell scripts. This count includes only code written by SAIC and its subcontractors, and the complete *IAS* software is very much larger (including the X Window System, the DBMS, NCAR graphics, the natural-language interface underlying *iastalk*).

In each of the three classes we give the size (in kilobytes, KB), the number of files, the total lines of code, the number of lines of comments, and the lines of executable code. These are estimates, considered to be accurate within 10%. The difference between the number of total lines and the sum of comments and executable code is primarily makefile lines.

Among the interesting features of the data in the table is that about one-third of the system is included in libraries (primarily for database access and graphics) which are shared by multiple processes. This is an indication of the efficiency of the implementation. Also, there are about 2 lines of comments for each 3 lines of executable code, which is evidence of good coding practice.

	Source Code	Libraries	Include Files	Shell Scripts	Total
KB	4,000	1,600	300	900	6,800
Files	829	246	179	210	1,464
Total Lines	132,000	56,000	10,000	10,000	208,000
Comments	55,000	19,000	3,500	3,500	81,000
Executable	65,000	35,000	6,000	6,000	112,000

IV FUNCTIONAL DESCRIPTION

4.1. INTRODUCTION

The overall architecture of the *IAS* was described in Section II in terms of the basic functions done by each element of the system. In this section we look in more detail at how these functions are accomplished. That is, we describe the algorithms, procedures and rules applied to the data during the processing. The subsections are listed below with a description of their relationship to the elements in the high-level dataflow (Figure 2.1) and software architecture diagrams (Figure 3.1).

4.2 **Signal Processing**
This functional element is clearly identified in Figure 2.1. It is done by the *SigPro* module of Figure 3.1.

4.3 **Expert System for Location**
This functional element is clearly identified in Figure 2.1. It is done by the *ASSESS* module of Figure 3.1.

4.4 **Script Matching and Acquisition**
Script matching is part of the "Event Location" and "Event Identification" elements of Figure 2.1. These functions are done by the *ScriptMatch* module in Figure 3.1. Script acquisition is part of the "Knowledge Acquisition" element (Figure 2.1), and it is done in the *SAS* module (Figure 3.1).

4.5 **Event Identification**
This function is clearly identified in Figure 2.1. The modules used for this function include *EventId, MERSY*, and *Sratio*.

4.6 **Analyst Review**
This covers the "Interactive Analyst Review" function of Figure 2.1. The software modules include all those listed in the "Analyst Review," "Display," and "Form Beams" boxes in Figure 3.1.

4.7 **Knowledge Acquisition**
This function is clearly identified in Figure 2.1. The software modules implementing it include *PerfV, SAS*, and *iastalk* (Figure 3.1).

4.2. SIGNAL PROCESSING

As described in Section 2.3, the initial step in the analysis of the data is to detect signals and compute features that characterize them, and this is done by the *SigPro* process described here. A dataflow description is given in Figure 4.1. The first two diagrams (Figures 4.1a and b) show the context and external interfaces. The two major functions done by *SigPro* are signal detection and post-detection processing, and these are described in Figures 4.1c and d.

As indicated in Figure 4.1a, *SigPro* is initiated by a command from an "Executive" process (*startSigPro*, see Section 3.3), and it is configured by parameters in the "Quasi-Static Data." *SigPro* communicates with other processes via IPC messages routed through a "Dispatcher." At the next level of decomposition (Figure 4.1b), we show that detection leads to selection of waveform "Segments" for post-detection processing to extract the detection attributes and other characteristics. Further decomposition in Figures 4.1c and d shows the major operations applied to the data.

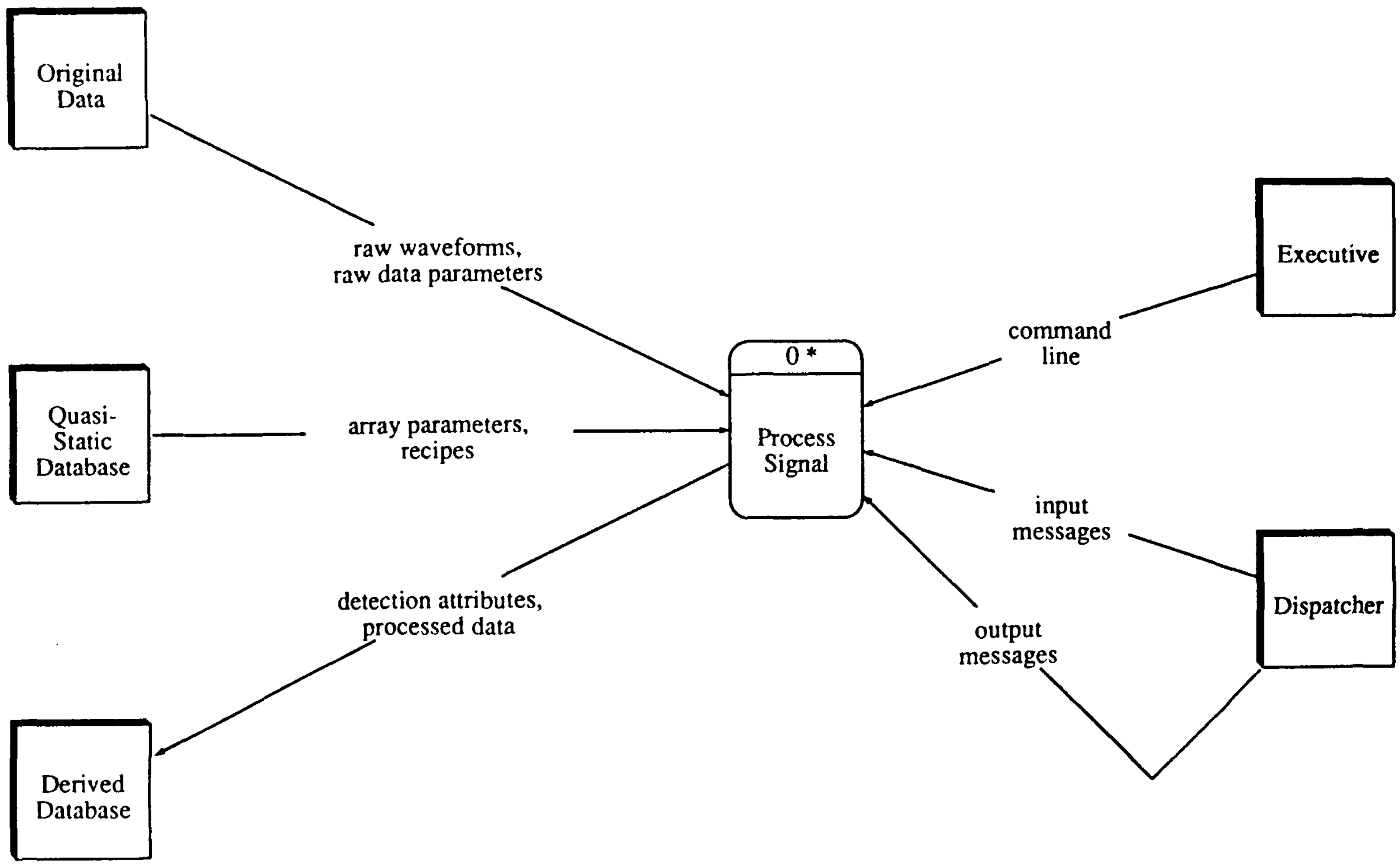


Figure 4.1a Context diagram for *IAS* signal processing.

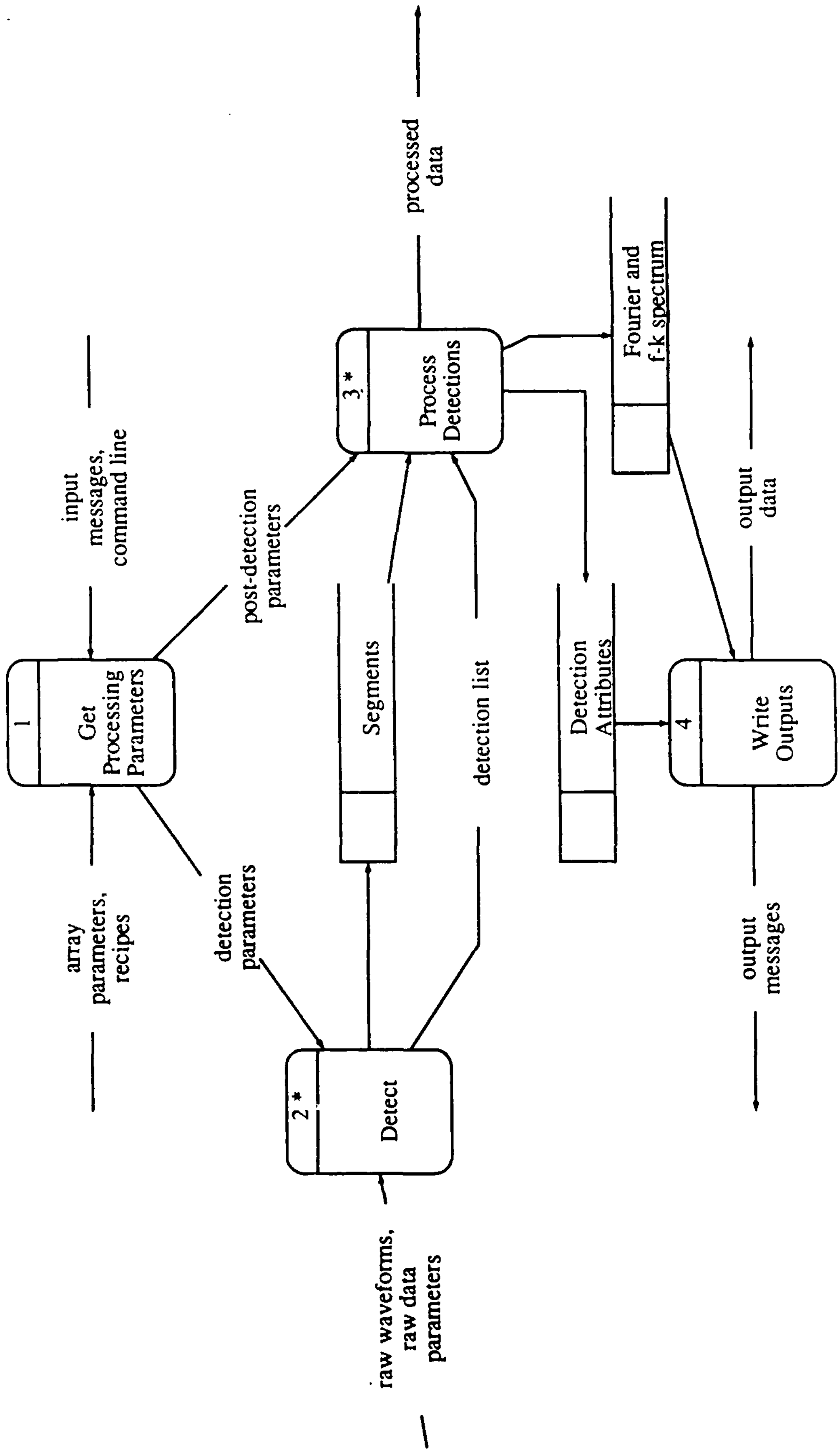


Figure 4.1b Signal processing overview. Boxes 2 and 3 are expanded in subsequent dataflow diagrams.

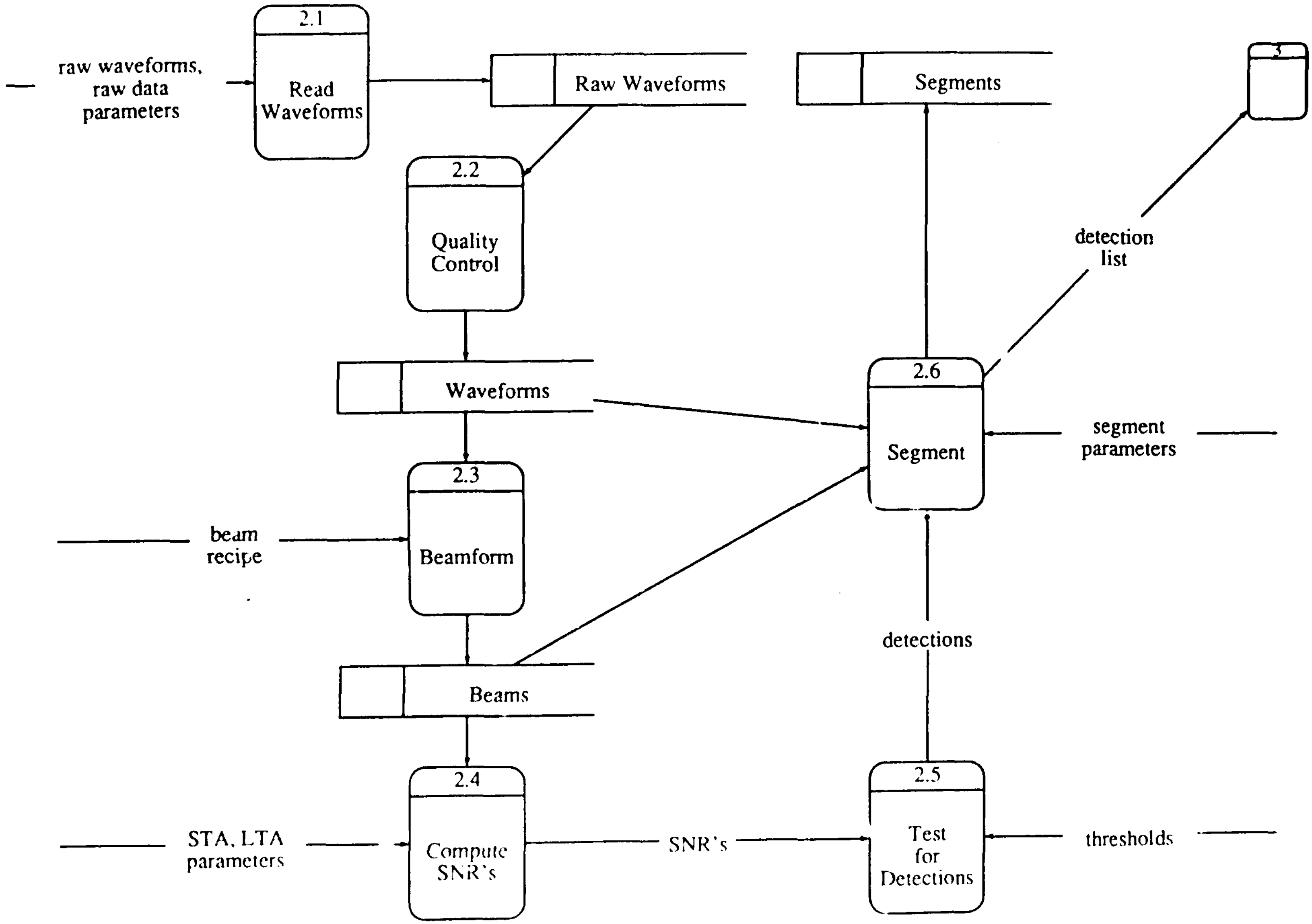


Figure 4.1c A dataflow description of the *IAS* detector.

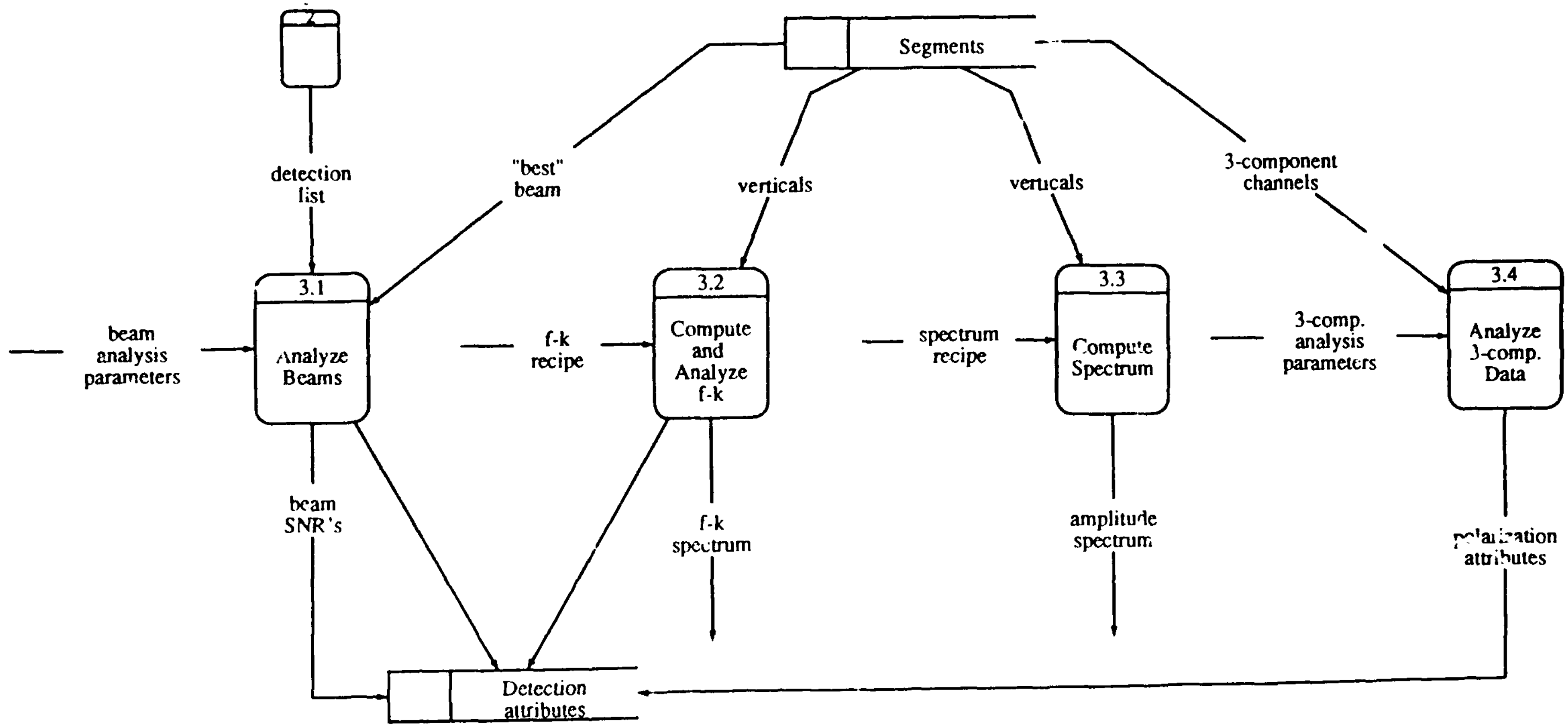


Figure 4.1d A dataflow description of *IAS* post-detection processes.

The *SigPro* program evolved from the NORSAR *RONAPP* program (Mykkeltveit and Bungum, 1984). While the data handling and control flow were redesigned, most of the subroutines that operate on the data were adapted unchanged from *RONAPP*. The other significant changes and additions include:

- Beamforming and detection using available horizontal channels has been added to *SigPro*.
- *SigPro* computes the spectrum of each detected signal and a preceding noise segment.
- The f-k power contours are analyzed to assign an estimate of the error in the slowness and azimuth estimates. This error depends, in part, on a measure of the "quality" of the f-k solution which is determined automatically.
- The original *RONAPP* computed f-k at a single frequency, but *SigPro* (and more recent versions of *RONAPP*) compute f-k averaged across a band of frequencies.
- *SigPro* computes various measures of the polarization of the detected signal.

In the remainder of this section we describe the particular algorithms implemented in *SigPro*. However, we emphasize that the modular design of *SigPro* isolates the major algorithms in modules designed to be upgraded or replaced with little or no alteration to other parts of the code.

4.2.1. Input Data

The data input to *SigPro* include the raw waveforms obtained from the "Disk Loop" (Figure 3.1) and parameters and recipes to configure *SigPro* for the particular array being processed. That is, applying *SigPro* to data from a different array is easily done by changing the appropriate quasi-static data. The original waveforms are managed with the .wfdisc and .w entities in Version 2.8 of the Center for Seismic Studies Database Structures† (Brennan, 1988). The quasi-static data are in tables in the 2.8 database and include the following:

- The location of each element of the array.
- Recipes specifying details of the quality control algorithms.
- Recipes specifying the beams to be calculated, the f-k calculation, the spectrum calculation, and the polarization calculation.
- Coefficients specifying various filters available for use.
- Parameters specifying the detection threshold for each filtered beam.

4.2.2. Beamforming and Detection

The waveform data are acquired by *SigPro* in large blocks selected by *SPServer* (Section 3.2), with the length typically varying between 30 and 120 minutes. *SigPro* first examines the data quality in 4 second segments to identify and repair or mask bad data. The latter is done by NORSAR subroutines developed by Jan Fyen. Each channel is examined for spikes‡ and series of zeroes or identical data. If the number of faulty values is less of all values in the segment, the faulty values are repaired by setting them to zero. Otherwise, the channel is masked for that 4-second segment (i.e., it is excluded from subsequent processing).

† Subsequently called "2.8 database."

‡ For spike detection the maximum amplitude within the 4-second segment is found for each element of the array, and these values are averaged across all channels. A spike is declared when the amplitude of a particular sample is more than 3 times larger than this mean maximum amplitude.

Specification of the beams to be computed is obtained from the quasi-static data on each initiation of *SigPro*. The particular beam set applied to ARCESS and NORESS during the 1989 operation of *IAS* is described in Table 4.1. For each of the 74 beams we give the steering azimuth and velocity, filter frequency band, filter order (for a Butterworth filter), beam type (C for coherent vertical beam, I for incoherent vertical beam, H for beam of horizontal channels), array elements included in the beam,‡ and SNR detection threshold. Selection of the vertical beam set is based on work done by Kværna (1989). Eight of these beams (#67 through #74) are selected for P waves from the major Soviet test sites at Novaya Zemlya and Semipalatinsk, and the other 62 are selected for regional phases.

The coherent beams are formed by simple delay-and-sum operations, followed by band pass filtering. For the incoherent beams each channel is first filtered, then rectified, delayed (if the beam is steered) and summed.† The horizontal beams are computed by simply summing all horizontal channels after filtering and rectifying (i.e., incoherent beams). The computational time required for a beam is roughly proportional to the number of channels filtered, so the incoherent beams are much more expensive to compute. Note that relatively few of them are included in the *IAS* beam set.

An STA/LTA detector is applied to each of the computed beams. The STA is updated every time sample (0.025s sampling rate) as the running average of the rectified beam amplitude over a 1-second time window. The LTA is computed from:

$$lta_{new} = lta_{old}\,(1. - 2^{-n}) + sta_{old}\,2^{-n}$$

For *IAS* n=5 and the *lta* is updated each 0.5 seconds, making the LTA an average over roughly 30 seconds.

For each beam the SNR = STA/LTA, and a detection is declared when SNR exceeds the specified threshold (Table 4.1). Often, numerous beams exceed their detection threshold in the same 4-second time segment. The beam with the largest value of SNR is taken as the "detecting" beam. The earliest detecting beam in this time segment also plays a role in subsequent processing, since its detection time is used as the initial estimate for the onset time (see Section 4.2.3.1). A beam in a detecting state remains in that state until the SNR stays below the beam threshold for an entire 4-second segment.

The result of this processing is a detection list including the STA, SNR, and detection time. This is passed to the next stage, the post-detection processing.

4.2.3. Post-Detection Processing

As shown in Figure 4.1d, this part of the processing has four major elements. Each of these is described in subsequent sub-sections.

4.2.3.1. *Analyze Beams*

The objectives here are to refine the detection onset time and estimate the dominant frequency and amplitude of the detecting beam and to determine the amplitude of the detection on a set of standard beams. The detection time onset (*time*) is estimated with the algorithm used in *RONAPP* (Mykkeltveit and Bungum, 1984) which analyzes the waveform peaks and troughs near the detection. In most cases the waveform analyzed is the "detecting" (i.e., largest SNR)

‡ The array geometry is shown in Figure 1.1. The center element is A0, and there are 3, 5, 7 and 9 elements in the A, B, C and D rings. Three-component sensors are at A0 and in the C ring.

† Steering delays are not used in the incoherent beams of Table 4.1, since they do not improve SNR at these frequencies and for this element spacing.

TABLE 4.1
IAS Beam Deployment

#	BEAM (Bmn)	VEL (km/s)	FILTER (Hz)	FILTER ORDER	AZIMUTH DEGREES	BEAM TYPE	THRESHOLD	RING SUBSET
1	221	∞	2.0-4.0	3	0.	H	2.4	A0 C
2	223	∞	5.0-10.0	"	0.	H	2.4	A0 C
3	226	∞	3.5-5.5	"	0.	H	2.4	A0 C
4	228	∞	8.0-16.0	"	0.	H	2.5	A0 C
5	201	∞	1.0-3.0	"	0.	C	4.0	A0 C D
6	202	∞	1.5-3.5	"	0.	C	4.0	A0 C D
7	207	∞	8.0-16.0	"	0.	C	4.5	A0 A B
8	220	∞	1.5-2.5	2	0.	I	2.5	A0 C
9	225	∞	3.5-5.5	3	0.	I	2.4	A0 C
10	254	∞	2.0-4.0	"	0.	C	4.0	A0 C D
11	261	∞	2.5-4.5	"	0.	C	4.0	A0 B C D
12	288	∞	3.0-5.0	"	0.	C	4.0	A0 B C D
13	275	∞	3.5-5.5	"	0.	C	4.0	A0 B C
14	282	∞	4.0-8.0	"	0.	C	4.0	A0 B C
15	289	∞	5.0-10.0	"	0.	C	4.5	A0 B C
16	310	∞	1.0-2.0	2	0.	I	2.5	A0 C
17	312	∞	2.0-4.0	3	0.	I	2.4	A0 C
18	313	∞	2.0-3.0	2	0.	I	2.5	A0 C
19	248	11.0	1.5-3.5	3	30.	C	4.0	A0 C D
20	249	""	""	"	90.	C	4.0	A0 C D
21	250	""	""	"	150.	C	4.0	A0 C D
22	251	""	""	"	210.	C	4.0	A0 C D
23	252	""	""	"	270.	C	4.0	A0 C D
24	253	""	""	"	330.	C	4.0	A0 C D
25	255	10.1	2.0-4.0	"	30.	C	4.0	A0 C D
26	256	""	""	"	90.	C	4.0	A0 C D
27	257	""	""	"	150.	C	4.0	A0 C D
28	258	""	""	"	210.	C	4.0	A0 C D
29	259	""	""	"	270.	C	4.0	A0 C D
30	260	""	""	"	330.	C	4.0	A0 C D
31	262	8.5	2.5-4.5	"	30.	C	4.0	A0 B C D
32	263	""	""	"	90.	C	4.0	A0 B C D
33	264	""	""	"	150.	C	4.0	A0 B C D
34	265	""	""	"	210.	C	4.0	A0 B C D
35	266	""	""	"	270.	C	4.0	A0 B C D
36	267	""	""	"	330.	C	4.0	A0 B C D
37	264	10.5	3.0-5.0	"	30.	C	4.0	A0 B C D
38	270	""	""	"	90.	C	4.0	A0 B C D
39	271	""	""	"	150.	C	4.0	A0 B C D
40	272	""	""	"	210.	C	4.0	A0 B C D
41	273	""	""	"	270.	C	4.0	A0 B C D
42	274	""	""	"	330.	C	4.0	A0 B C D

TABLE 4.1
(continued)

# #	BEAM (Bmn)	VEL (km/s)	FILTER (Hz)	FILTER ORDER	AZIMUTH DEGREES	BEAM TYPE	THRESHOLD	RING SUBSET
43	276	11.1	3.5-5.5	3	30.	C	4.0	A0 B C
44	277	""	""	"	90.	C	4.0	A0 B C
45	278	""	""	"	150.	C	4.0	A0 B C
46	279	""	""	"	210.	C	4.0	A0 B C
47	280	""	""	"	270.	C	4.0	A0 B C
48	281	""	""	"	330.	C	4.0	A0 B C
49	283	9.4	4.0-8.0	"	30.	C	4.0	A0 B C
50	284	""	""	"	90.	C	4.0	A0 B C
51	285	""	""	"	150.	C	4.0	A0 B C
52	286	""	""	"	210.	C	4.0	A0 B C
53	287	""	""	"	270.	C	4.0	A0 B C
54	288	""	""	"	330.	C	4.0	A0 B C
55	290	10.4	5.0-10.0	"	30.	C	4.5	A0 B C
56	291	""	""	"	90.	C	4.5	A0 B C
57	292	""	""	"	150.	C	4.5	A0 B C
58	293	""	""	"	210.	C	4.5	A0 B C
59	294	""	""	"	270.	C	4.5	A0 B C
60	295	""	""	"	330.	C	4.5	A0 B C
61	296	9.9	8.0-16.0	"	30.	C	4.5	A0 A B
62	297	""	""	"	90.	C	4.5	A0 A B
63	298	""	""	"	150.	C	4.5	A0 A B
64	299	""	""	"	210.	C	4.5	A0 A B
65	300	""	""	"	270.	C	4.5	A0 A B
66	301	""	""	"	330.	C	4.5	A0 A B
67	302	15.9	1.5-3.5	"	80.	C	3.5	A0 A B
68	303	""	2.0-4.0	"	80.	C	3.5	A0 A B
69	304	""	2.5-4.5	"	80.	C	3.5	A0 B C D
70	305	""	3.0-5.0	"	80.	C	3.5	A0 B C D
71	306	10.0	1.5-3.5	"	30.	C	3.5	A0 C D
72	307	""	2.0-4.0	"	30.	C	3.5	A0 C D
73	308	""	2.5-4.5	"	30.	C	3.5	A0 B C D
74	309	""	3.0-5.0	"	30.	C	3.5	A0 B C D

beam, but the quasi-static data provide for selection of a different beam when appropriate. In *IAS* the quasi-static data select for analysis the closest vertical coherent beam (i.e., similar or identical filter and element subset) when the detecting beam is incoherent (vertical or horizontal).

SigPro also provides an estimate of the error in *time*. This varies from 4.0 seconds when the SNR on the detecting beam is at the threshold to 1.0 seconds when it is 5 or more times larger than the threshold. This estimate is treated as the 1σ error bound on the onset time in subsequent location calculations.

A consistent measure of amplitude is needed for subsequent stages of the interpretation. Thus, a set of standard beams is designated (in *IAS* these are beams 5, 7, 10, 14, 16, 17 of Table 4.1), and the maximum STA is determined for each within a four-second window surrounding the *time* determined from the waveform analysis. These STA and the corresponding LTA are stored in the DBMS.

4.2.3.2. *Frequency-Wavenumber Analysis*

The f-k calculation is configured with quasi-static data, and here we describe how it is done in *IAS*. For each detection the f-k power spectrum is computed for a 3 second segment starting 1.1 seconds before the onset time. The computation is done with all available (up to 25 for NORESS and ARCESS) vertical channels after band-pass filtering each channel. The wide-band f-k algorithm of Kværna and Doornbos (1986) is used. The power spectrum (P) is computed from:

$$P(sx,sy) = \frac{\sum_{f=f1}^{f=f2} \left(\sum_{ich=1}^{ich=nch} F(f,ich) \exp^{i\,2\pi f\,(sx\,x\,+\,sy\,y)} \right)^2}{\sum_{f=f1}^{f=f2} nch \sum_{ich=1}^{ich=nch} F(f,ich)^2}$$

where sx is the E-W slowness, sy the N-S slowness, F(f,ich) the Fourier transform of channel ich at frequency f, x & y the E-W and N-S coordinates of the channel relative to the array reference station, f1 and f2 the low and high frequency limits, and nch the number of channels.

The frequency band for the calculation is one octave centered over the dominant frequency determined by the waveform analysis described above. The resolution is 41×41 points and .02 sec/km in slowness. Estimates for the azimuth and slowness of the detected signal are obtained by interpolation around the peak power. The error in these estimates depends on the wavenumber resolution in this frequency band and the quality of the particular solution. To estimate the resolution, we analyze the theoretical beam pattern to find the difference between the azimuth and slowness values at the peak power and their values at 1 dB below the peak. For a symmetric array like NORESS the 1 dB contour is a circle. If the radius of this circle is δk, the errors in azimuth ($\delta\alpha$) and velocity (δv) at the center frequency f_c are:

$$\delta\alpha = \sin^{-1} \left(\frac{v}{f_c}\right) \delta k$$

and

$$\delta v = \frac{v^2}{f_c}\,\delta k$$

To account for additional errors caused by noise, interfering signals, and deviation from the plane-wave assumption, we also compute an f-k quality measure, *fkq*. For this we follow NORSAR conventions (Ringdal, personal communication) and set $fkq = 1$ when the amplitude of the second highest peak is more than 6 dB less than that of the highest peak (maximum f-k power). The *fkq* is 2, 3, and 4 when the difference between the first and second peaks is 4 to 6 dB, 2 to 4 dB, and 0 to 2 dB, respectively. An F-statistic (*fstat*) is also computed (Kværna, personal communication) to characterize the coherency of the f-k power spectrum as follows:

$$fstat = \frac{fk_{max}}{(p_{ave} - fk_{max})}$$

where fk_{max} is the maximum f-k power, and p_{ave} is the average power in the n vertical-channel time-series. The *fstat* can have any positive value, but the values archived range between 0 and 99.99, with the latter representing all $fstat \geq 99.99$.

The resolution error and *fkq* are combined to obtain slowness and azimuth error estimates used in subsequent parts of the *IAS* processing. When *fkq =1*, the resolution error is interpreted to be 2 standard deviations (2σ). When *fkq=2* the error is 1.5σ, and when *fkq=3*, the resolution error is interpreted to be σ. Detections with *fkq=4* are considered to be essentially noise, and they are not used in further processing. The correspondence between these *ad hoc* error estimates and a statistically meaningful standard deviation is not supported rigorously, and the validity of the estimates will be reviewed when enough operational experience is accumulated.

4.2.3.3. *Spectra Computation*

Spectra are calculated for each detection and a preceding noise segment using the method of Bache *et al.* (1985). The signal spectrum is calculated for a 5 second window starting 0.3 seconds before the onset time on the center element of the array (no corrections are made for time delays across the array). Power spectra are computed for each vertical channel and averaged. A similar power spectrum is computed for a 5-second noise segment selected 12 seconds before the onset time. Both signal and noise amplitude spectra are saved for future processing.

4.2.3.4. *Polarization Analysis*

As with the other post-detection processes, the parameters controlling details of the polarization analysis are specified by quasi-static data, and they are easily changed. Here we describe the details of the polarization calculations done during *IAS* operation in 1989. The method is that of Jurkevics (1988), modified for automated application in *SigPro*. In this method the time-domain polarization ellipse is computed by solving the eigenproblem for the covariance matrix. Data from the four three-component sensors at NORESS and ARCESS are combined by averaging the individual covariance matrices before solving the eigenproblem.

The polarization analysis is performed on an 8 second data segment starting 4 seconds before the onset time of the signal at the center element of the array. There is no time shifting to account for phase velocities across the array, though this is possible at this stage of the processing using results from the f-k analysis. Numerical experiments done by Jurkevics (1988) indicate that the covariance averaging is not very sensitive to time delays across the array at frequencies of interest.

The covariance matrices are computed in the time domain for a series of frequency bands, then normalized and averaged to obtain a wide-band estimate. For *IAS* the emphasis is on regional signals, and the selected frequency bands are 1-2, 2-4, 4-8, and 8-16 Hz. In each frequency band the covariance matrices are calculated for each seismometer for thirteen 2-second overlapping (by 1.5 seconds) tapered time windows. These are then averaged across all available three-component seismometers in the array to obtain covariance matrices for the 4 frequency bands and 13 time samples. A pre-event noise segment selected 20 seconds before the onset time is processed the same way, and the noise in each frequency band N(f) is taken as the maximum three-component amplitude occuring in the 13 time samples. In each frequency band a signal/noise (SNR) is computed as the ratio of the maximum three-component amplitude occuring in the signal to the maximum three-component amplitude occuring in the noise. The covarience matrices for those frequency bands that are above a specified SNR threshold (1.5) are then normalized (by the trace) and averaged to obtain wide-band covariance matrices for the 13 time samples. The polarization ellipsoid is then computed for each of these 13 times.

Various parameters are calculated from the eigenvalues of the polarization ellipsoid to characterize the particle motion. Several parameters are calculated from the time window with the maximum rectilinearity. These are the rectilinearity, the apparent incidence angle, and the time of the center of this window. Also, the window with the maximum three-component amplitude is found, and the horizontal/vertical amplitude ratio and incidence angle of the smallest eigenvalue are saved with the time of the center of that window. Also saved is the maximum SNR found for the four frequency bands.

4.2.4. Output Data

The data output by *SigPro* for each detected signal are as follows:

- The onset time, amplitude and period of the detected signal.
- The STA and LTA (short-term and long-term averages) at the onset time for a standard beam set.
- The "detecting" beam: i.e., maximum signal/noise (SNR) beam.
- The azimuth and slowness determined from analysis of the f-k power contours.
- Error estimates for the onset time (based on SNR), azimuth and slowness (based on analysis of the f-k power contours).
- Measures of the f-k solution quality.
- The f-k power contours.
- The Fourier spectrum of the signal and a preceding noise segment.
- Particle-motion attributes obtained from polarization analysis of the signal.

4.3. EXPERT SYSTEM FOR LOCATION

Section 2.3 described the conceptual design of the expert system which interprets the output of *SigPro* to locate seismic events, and this is done in the *ASSESS* software module (Figure 3.1). In this section we describe the *ASSESS* inference structure and the specific rules and procedures (the "knowledge base") used for *IAS* processing during October-December, 1989. A key advantage of an expert system software architecture is the separation of the knowledge base from the inference structure, so it is relatively easy to add new knowledge as it is obtained. Thus, the details of the rules and procedures described here are changing with experience.

The reasoning process employed by *ASSESS* is sketched in Figure 4.2. The input are the "features" computed by *SigPro*. The figure highlights the fundamental division between "single-array processing" which is done first and considers only the information provided by one array, and "network processing" which combines information from all stations in the network (two arrays in *IAS*). Within the single-array processing the reasoning proceeds in order through the four major elements shown. This provides a natural segmentation of the knowledge base that reduces the scope (i.e., number of relevant rules) of the reasoning at any given time. The single-array processing provides a tentative identification of each detected signal and a single-array location for appropriate groups of signals. The reasoning in "network processing" involves an iterative comparison of results from different stations to seek corroborating data and backtracking to revise earlier solutions (including those from the single-array processing). In subsequent sections we describe the rules and procedures within each of these major divisions.

The reasoning strategy of *ASSESS* generates and explores hypotheses in a depth-first manner starting from the most simple explanations of the data. That is, at each stage of the processing shown in Figure 4.2 the *simplest explanation* of the data is hypothesized (e.g., all phases from nearly the same azimuth are from the same event), and knowledge is used to search for contradictions to this hypothesis (e.g., there is a P phase after an S phase, so there cannot be only one event). When contradictions are encountered, the hypothesis is retracted, and the next simplest hypothesis is examined (e.g., there are two events). This strategy works well for the regional seismic problem, and it matches reasonably well the reasoning process applied by a human analyst.

4.3.1. Features -- Data Input to *ASSESS*

The specific data input to this program include:

sta	Station identifier
bmtyp	The "detecting" beam (Section 4.2.2)
stav	Short-term average from the "detecting" beam (Section 4.2.2)
snr	Signal/noise on the "detecting" beam (Section 4.2.2)
time	Onset time from the waveform analysis (Section 4.2.3.1)
deltim	Assumed standard deviation on the onset time (Section 4.2.3.1)
amp	Short-term average from standard beam #17 (Table 4.1), a 2-4 Hz incoherent beam of the A0 and C ring vertical channels (Section 4.2.3.1)
seaz	Azimuth from f-k processing (Section 4.2.3.2)
delaz	Assumed standard deviation on the azimuth (Section 4.2.3.2)
vel	Inverse of the slowness from f-k processing (Section 4.2.3.2)

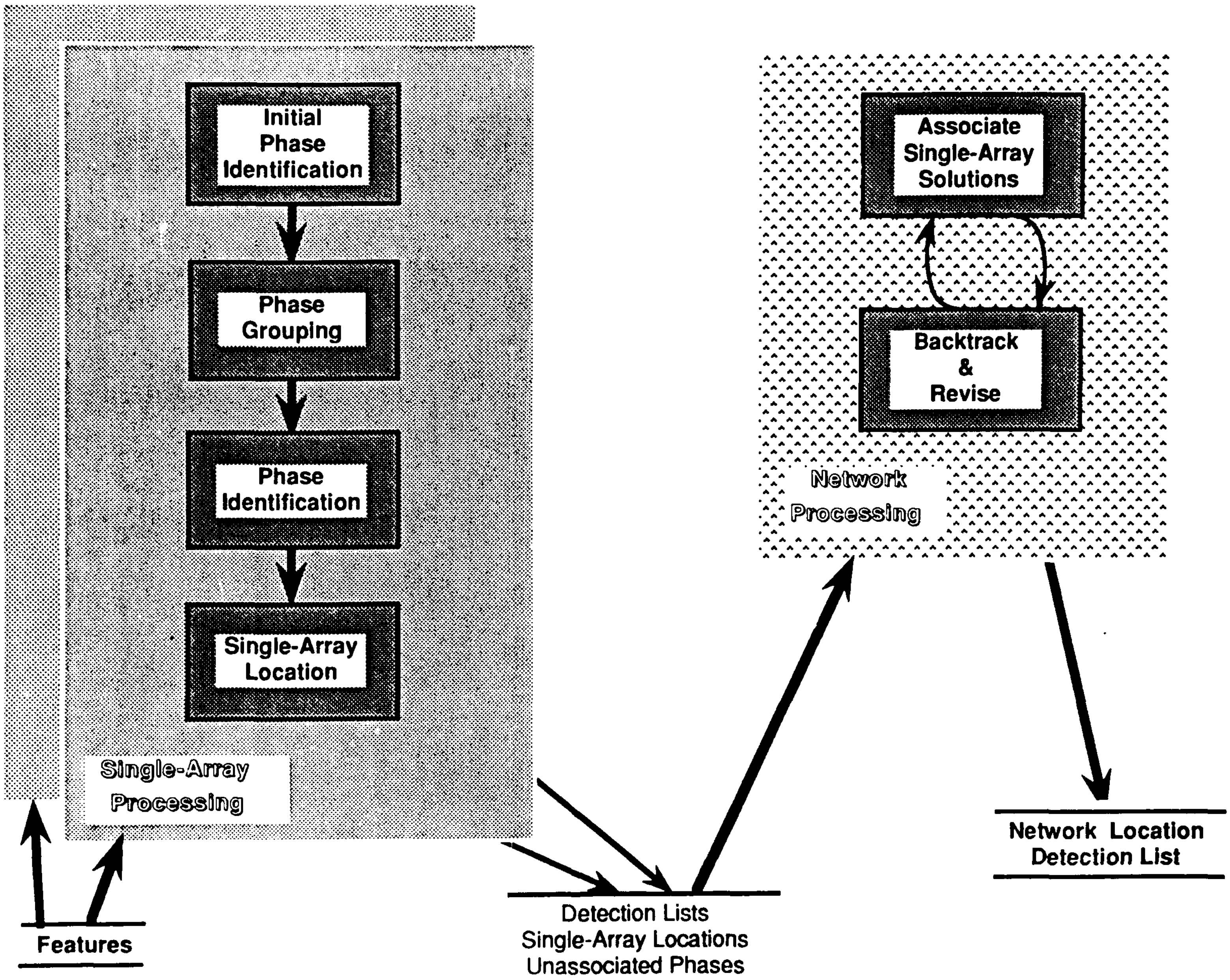


Figure 4.2. A high-level view of the reasoning process employed by *ASSESS* is shown. The major steps in the single-station processing are shown in the order they are taken. The network processing is more complex, and it is sketched in somewhat more detail in Figure 4.3.

fkqual	f-k solution quality (the *fkq* of Section 4.2.3.2)
rect	Rectilinearity from polarization analysis (Section 4.2.3.4)
inang1	P incidence angle from polarization analysis (Section 4.2.3.4)
hvrat	Horizontal/vertical ratio from polarization analysis (Section 4.2.3.4)
inang3	Short-axis incidence angle from polarization analysis (Section 4.2.3.4)

4.3.2. Single-Array Processing

ASSESS takes as input a detection list ordered by time, but the single-array reasoning described here takes account of the array identifier (*sta*), effectively considering only detections from the same array. This single-array reasoning process and knowledge are described in this section.

4.3.2.1. *Initial Phase Identification*

A major simplification of the interpretation task is possible with data from NORESS-type arrays because the phase velocity determined from the f-k analysis provides a reliable separation between P-type and S-type phases. As noted by Mykkeltveit and Bungum (1984) and verified by subsequent experience, the phase velocity 6 km/sec provides almost perfect separation between regional Pn and Pg and regional Sn and Lg. In our experience there are no exceptions to this rule for *fkqual* < *4*. For this and other reasons, detections with *fkqual*= *4* are marked as "noise" and are not used in the interpretation. The demarkation between teleseismic and regional P is not so simple, but we can assert with very high confidence that signals with estimated phase velocities > 14 km/sec are from teleseismic events. At the other end of the velocity range, signals with phase velocities ≤ 2.8 km/sec are almost always noise or late coda detections (not useful for location), so they can safel;' be marked as noise.

In summary, at this first stage of the interpretation we use the estimated phase velocity (*vel*) to assign the initial phase identification to each detected signal. The identification is:

N if $vel \leq 2.8$

S if $2.8 < vel \leq 6$

P if $6 < vel \leq 14$

T if $vel > 14$

Some of the signals called P will actually be teleseisms, and some of the phases called S will actually be noise. Some of these non-regional signals could be identified by applying more knowledge (e.g., frequency content), but this only reduces the number of phases that are candidates for later identification as Pn, Lg, etc. In the initial implementation this advantage did not warrent the added complexity.

4.3.2.2. *Detection Grouping*

The next step in the interpretation is to form groups of phases that appear to be generated by the same event. Only phases identified as P or S are considered. The first step is to form an "initial detection grouping" to provide a focus of attention. The rule is:

- *Form Initial Detection Grouping*
  Each new detection is considered for inclusion in existing groups. It is included if it occurs within 6 minutes of the last detection in a group and its azimuth overlaps (within $\pm 2.5*delaz$ bounds on each) with the azimuth of the first detection in the group. Otherwise, a new group is formed.

The number of events contributing phases to this "initial detection grouping" could be as few as one, or as many as there are separate P and S phases in the group. The simplest explanation is that there is only one event, and this is taken as the initial hypothesis. Contradictions to this hypothesis are sought, indicating that there are at least two events in the group. In the 1989 implementation, the maximum number of events *ASSESS* will find in the "initial detection grouping" is two. This becomes a limitation when there are three or more events at the same azimuth contributing phases spaced by no more than 6 minutes. New rules will be introduced to deal with this in future versions. The tests applied to determine whether there are one or more events in the initial detection grouping are as follows:

- *Test for P after S*
  A P phase occuring after an S phase must be from a different event.
- *Inconsistent P detections*
  Find the first P and largest S in the group. Using the travel-time tables assuming the first P is Pn and the largest S is Lg, determine the time separation between Pn and Pg (*Pn-Pg*) and Sn and Lg (*Sn-Lg*). If the time separation between any two P phases is more than 1.5*(*Pn-Pg*), these two phases are assumed to be from different events.
- *Inconsistent S detections*
  Use the *Sn-Lg* defined in the previous rule. If the time separation between any two S phases is more than 1.5*(*Sn-Lg*), these two phases are assumed to be from different events.

The next step is to assign each P and S phase to an "event group." When the previous rules conclude that there is more than one event contributing detections to the "initial detection grouping," there are often many potentially correct combinations of P and S phases. The objective of the next set of rules is to find the combination most likely to be correct.† A significant simplification of the problem is made by collecting one or more closely-spaced phases of the same type (P or S) into *bins*. Individual phases in the *bins* retain their individual identity, but it is sometimes convenient to treat a *bin* as a single phase (e.g., a phase and following coda detections). The rules for forming the *bins* and associating them with specific events are as follows:

- *P bin rule #1*
  There is one *P bin* for each "different" event from the *Inconsistent P detections* rule. This *P bin* includes all P consistent with the first P in the bin.
- *P bin rule #2*
  When there are two events and two or more P waves not separated by *P bin rule #1*, the last P is placed in a second *P bin*.
- *S bin rule #1*
  There is one *S bin* for each "different" event from the *Inconsistent S detections* rule. This *S bin* includes all S consistent with the first S in the bin, and overlapping with largest S in azimuth (azimuths agree within ±2.5**delaz* bounds on each). Arrivals that do not satisfy these time and azimuth constraints are placed in a second *S bin*.
- *S bin rule #2*
  When there are two events and two or more S waves not separated by *S bin rule #1*, the last S is placed in a second *S bin*.

† In many cases it is not possible even for a skilled human analyst to unravel mixed signals with high confidence using only data from a single array. Detections from another station or array are needed.

These rules result in ≥ 1 *P bins* and ≥ 1 *S bins*. To separate these into events we apply the following rules:

- *Bins of only one type (P or S)*
  All phases are marked unassociated, and there will be no event at the single-array stage of the processing.
- *One P bin or only one S bin and ≥ 1 bin of the other type*
  There is one event. If there is only one *P bin*, it is associated with the *S bin* containing the largest amplitude (*amp*) S, and the phases in all other *S bins* are marked unassociated. If there is only one *S bin*, it is associated with the earliest *P bin*, and the phases in all other *P bins* are marked unassociated.
- *≥ 3 P bins and ≥ 3 S bins*
  Associate the first *P bin* and the *S bin* containing the largest amplitude S (*amp*). Mark all phases in other *bins* unassociated.

If there are ≥ 2 *P bins* and 2 *S bins* or ≥ 2 *S bins* and 2 *P bins*, there is assumed to be two events. Phases are associated to form these two events using the following rules:

- *P after S*
  A P that follows an S is the first P phase for the second event.
- *Complete event group preference*
  A complete event group must have at least one *P bin* and one *S bin*. When there are two of each reject combinations that leave unassociated phases or *bins*.
- *Associate phases or bins using amplitude or azimuth*
  P and *S bins* are separated with amplitude if the largest amplitude (*amp*) in the two *bins* differs by at least a factor of two. In this case the largest *P bin* is associated with the largest *S bin*. Otherwise, associate the *P bin* and *S bin* which have maximum amplitude phases with azimuths least different.

At the end of this stage of processing *ASSESS* has the phases divided into *event groups* with each containing at least one P and one S phase. Phases not included in an *event group* may later be associated with events during the network processing.

4.3.2.3. *Phase Identification*

At least two phases must be identified as Pn, Pg, Sn, Lg, or Rg (together with their azimuths) to locate an event with data from a single array. At the *phase identification* stage at least two of these "locating phases" are selected from the phases in each *event group*. The appropriate rules vary significantly with region, and the current set is only appropriate for the region around NORESS and ARCESS.

These rules separate the event groups into three classes depending on their apparent range from the array. This is based on *S-P*, which is the arrival time separation between the first P and largest S in the *event group*. The rules also use the apparent polarization which is represented by integers (*Ppolar* and *Spolar*) computed from *rect*, *inang1*, *hvrat*, and *inang3* as indicated in the tables below. When $snr \leq 2$, *Ppolar* and *Spolar* are set to zero (undetermined polarization). Otherwise, the negative values indicate Pg or Lg polarization, while positive values indicate Pn or Sn polarization. The larger the value, the stronger the polarization.

Ppolar

	rect≤0.55	0.55<*rect*≤0.8	*rect*>0.8
incng1>50	0	-1	0
30<*inang1*≤50	0	0	1
inang1≤30	0	1	1

Spolar

	hvrat≤1.	1.<*hvrat*≤1.5	1.5<*hvrat*≤2.	*hvrat*>2.
inang3>60	-3	-2	0	0
35<*inang3*≤60	[illegible]	-1	0	0
10<*inang3*≤35	0	0	1	2
inang3≤10	0	0	2	3

The *phase identification* rules are listed below, divided into the three classes of *S-P* separation.

☐ *Event groups with S-P ≤ 30 sec*

- Largest S = Lg
- 1st P = Pg

☐ *Event groups with 30 sec < S-P ≤ 75 sec*

Pn or Pg:

Case 1: only 1 P

- If *Ppolar* ≤ 0, then P = Pg
- If *Ppolar* > 0, then P = Pn

Case 2: Two or more P and 1st P is largest

- If *S–P* ≤ 40 sec and 1st P *Ppolar* ≤ 0, then 1st P = Pg
- If *S–P* > 40 sec or 1st P *Ppolar* > 0 then, 1st P = Pn

Case 3: Two or more P and 1st P not largest

- 1st P = Pn
- If the *time* of largest P ≤ 12 seconds later than *time* of 1st P and largest P *Ppolar* < 0, then largest P = Pg

Sn or Lg:

Case 1: 1st S detected on horizontal beam with *Spolar* ≥ 0

- 1st S = Sn
- If the largest S is not the 1st S and has *time* S within 10 seconds of the predicted Lg time (Pn or Pg and Sn are already identified), then largest S = Lg
- If largest S *time* is more than 10 seconds from the predicted Lg time and S with smallest *Spolar* (if tied, select S with largest *amp*) has *Spolar* < *0* and *time* within 10

Sn or Lg

Case 1: All S detections are within 20 seconds

- If any S detected on horizontal beam with *Spolar* > 0, then 1st S = Sn
- If any S detected on horizontal beam or any S has *Spolar* > 0, then 1st S = Sn
- If no S detections on horizontal beam or no S with *Spolar* > 0 and 1st S *seaz* between 200 and 360 degrees at NORESS (100 and 250 degress at ARCESS), then 1st S = Sn
- If no S detections satisfy the above conditions, then Largest S = Lg

Case 2: S detections separated by more than 20 seconds

Separate the S detections into two sets at the largest gap.

- If first set has any S detected on horizontal beam or with *Spolar* > 0, then 1st S = Sn
- If *Spolar* < 0 for any S in 2nd set, then S with smallest *Spolar* (largest *amp* if tie) in 2nd set is Lg
- Largest S in 2nd set is Lg

4.3.2.4. *Location*

Seismic locations are computed with a version of the the TTAZLOC program (Bratt and Bache, 1988) converted into a function (called *LocSAT*) within *ASSESS*. This program module is used for all locations (single-array processing and network processing) in *ASSESS*, as well as elsewhere in the system (e.g., LocSAT is embedded in ARS, see Section 4.6). *LocSAT* uses backazimuth estimates, arrival-time data, and associated uncertainties in a least-squares-inverse location algorithm. The data input include the array locations, travel-time tables for the phases of interest (Pn, Pg, Sn, Lg, Rg), and the arrival-time and azimuth data (*time, deltim, seaz, delaz*) for each phase associated with the event.

The output returned by the *LocSAT* module includes the location solution (latitude, longitude, and origin time†) and the 90% confidence error ellipsoid. Also returned are the station-to-event location distance and azimuth for each locating station and the travel-time and azimuth residuals for each datum used in the location calculation.

The Bratt and Bache (1988) location procedure is an adaptation of the Jordan and Sverdrup (1981) formulation which allows the use of both *a priori* (*deltim* and *delaz*) and *a posteriori* (the solution residuals) information about the data uncertainties. Their relative contribution is controlled by the parameters K and s_K^2. In the 1989 *IAS* operation the values used were $K=8$ and $s_K^2 = 1.5$. These values make the confidence ellipsoids much more dependent on the assigned variances than on the solution residuals.

The Pn and Sn travel-time curves are computed from a P-wave model provided by Mykkeltveit (personal communication) shown below. The S-wave velocities in the crust are obtained by assuming a Poisson solid, and the mantle S velocities were estimated by Henry Swanger (SAIC) from 102 events recorded at NORESS and ARCESS.

† In *IAS* the depth is constrained to zero for all location calculations.

Thickness (km)	Vp (km/sec)	Vs (km/sec)
16.0	6.20	3.58
24.0	6.70	3.87
15.0	8.10	4.60
--	8.23	4.68

Other phases are assumed to have constant group velocity as follows:

Pg - 6.20 km/sec
Lg - 3.55 km/sec
Rg - 3.00 km/sec

This model is most appropriate for paths from NORESS to the east. Paths to the west and to ARCESS are known to be different, but no attempt is made to account for these differences in the first operational version of *IAS*. Data obtained by operating *IAS* for an extended period will allow development of excellent travel-time curves for the region.

4.3.3. Network Processing

At this stage *ASSESS* has interpreted the data from each array separately. Noise detections have been noted and removed from further consideration, teleseisms have been identified, and regional phases are identified as P or S. These "initial phase identification" decisions cannot be changed by subsequent processing with *ASSESS* (as currently implemented). Many of the P and S phases are associated with events, and each event includes at least one defining P (Pn or Pg) and at least one defining S (Sn or Lg).† An arbitrary number of other P and S phases may also be associated with an event, and most of them are detections in the coda of the defining phases. The detection list also includes many P and S phases that are not associated with an event, and these are called "unassociated P" (or S).

The objective of "network processing" is to fuse the information from the stations in the network (in this case, two arrays) to obtain a complete interpretation of the data. The general concept for the processing involves three steps: (1) start with solutions from one array; (2) seek collaboration from observations at the other array; and (3) resolve inconsistencies by backtracking to change earlier decisions. The goal is a consistent explanation of as many phases as possible. The processing requires computation of many location solutions as various hypotheses are explored. All locations, including the final network location, are computed with the *LocSAT* module described in Section 4.3.2.4.

The reasoning process is sketched in Figure 4.3. The various steps are described below.

Event Grouping

Pairs of single-station locations, one from each array, are candidates for grouping if their origin times are within six minutes. A pair is grouped if the location from one array has at least one defining phase consistent with a common origin for at least one defining phase from the location at the other array. Two defining phases are consistent if their arrival times fit a single origin within the area of overlap of the 2.5**delaz* bounds on the azimuths.

Check for Overlapping Ellipses

The ellipses from grouped single-station locations are compared to determine if their 90%

† The initial implementation of "phase identification" (Section 4.3.2.3) does not include rules for identifying Rg.

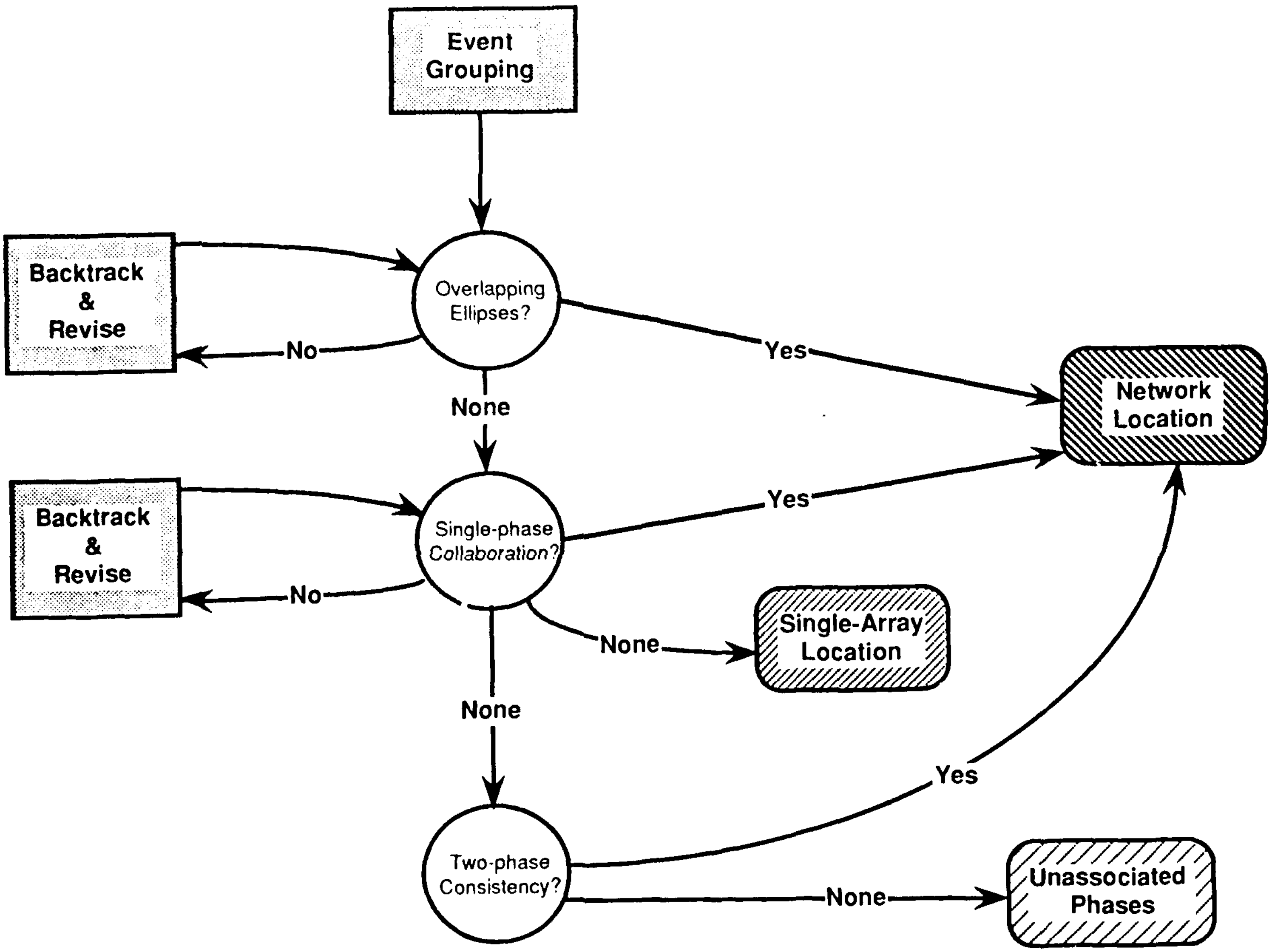


Figure 4.3. The reasoning used fo. network processing is outlined. The output of this processing is indicated in the three boxes on the right side of the figure.

confidence ellipsoids (latitude, longitude, origin time) overlap. If they do, the single-array locations are assumed to be correct (i.e., the associated phases are assumed to be identified correctly), and a network location is computed. If they do not, the next step is initiated.

Backtrack & Revise to Seek Overlapping Ellipses

First, the location nearest its locating array (array A) is assumed to be correct. The defining phases from the array B location are then revised by applying the rules listed below one-by-one in the order listed.

- Change Sn to Lg. If both Sn and Lg are already present, also change the current Lg to S.
- Change Lg to Sn. If both Sn and Lg are already present, also change the current Sn to S.
- Change Pg to Pn. If both Pn and Pg are already present, also change the current Pn to P.
- Change Pn to Pg. If both Pn and Pg are already present, also change the current Pg to P.

Each revision gives a new array B location, and this is tested to see if the new confidence ellipsoid overlaps with that from the array A location. If they do, these single-array locations are assumed to be correct, and a network location is computed. If the array B revision options are exhausted without success, the original array B solution is fixed, and the same revision rules are applied to the defining phases for the array A solution. If overlapping confidence ellipsoids are found, this set of phase identities is used for the network location.

As currently implemented, this backtracking is limited to revision of one defining phase from one array and elimination of at most one defining phase. There are no rules that allow changing undefining P or S into a defining phase, or that allow revision of defining phases at both arrays. If these revision options are exhausted without finding a pair of overlapping ellipsoids, the processing moves to the next step.

Check for Corroborating Phases

At this step individual phases from the other array are sought to corroborate the remaining single-station locations. Each single-station location is considered in order, based on origin time. The 90% confidence ellipsoid for this location (the "reference location") is used to compute the minimum and maximum arrival times for each defining phase at the other station. If any phase at the other station has arrival time within this time window, is of the correct type (e.g., P for Pn and Pg), and is not already a defining phase for another event, it is added to the reference location as a defining phase from the other array. If several phases satisfy these criteria, the one with arrival time closest to the center of the time window is chosen.

There are no limitations on the number (up to four) of corroborating phases found in this way, but usually there is only one. Occasionally, both Pn and Pg are found, and rarely both Sn and Lg are found. We would not expect to find a P-type and an S-type defining phase at this stage, since the phases that meet the conditions for corroboration would almost certainly have been identified already during single-station processing.

Backtrack & Revise to Seek Corroborating Phases

If the previous step finds no corroborating phases for the original single-station location, that reference location is revised using the same rules applied during backtracking with overlapping ellipsoids. These rules are applied one-by-one, and the process is terminated if one or more corroborating phases are found. The current reference location and corroborating phases are assumed to provide the correct interpretation, and the network location is computed. If all revision options are exhausted without finding a corroborating phase, the original single-station location is assumed to be correct.

Seek Two-Station, Two-Phase Events

At this step all remaining phases that have not been associated with an event are analyzed to define events with only one defining phase at each array. First, phases from one array are paired with phases at the other array if their arrival times are separated by less than six minutes. These pairs are considered one-by-one in order of origin time. For each pair the array with the earliest arrival time phase is chosen as the reference (array A). For each of the two possibilities (Pn and Pg if the array A phase is P, Sn and Lg if it is S), an origin time can be computed for any location in the area of overlap of the 2.5**delaz* bounds on the azimuths. With this origin time and the minimum and maximum epicentral distance with respect to the other array (array B), an arrival time window (T_w) is defined for phases at array B. When a phase falls within this window, a potential event solution has been found. There are four possible phase identification pairs, and more than one pair may satisfy these criteria. When this occurs, the ratio C/D is computed for each, using the travel-time of the phase at array B. In this ratio, C is the travel time between the estimated location and the point at the center of the area of overlap of the azimuth bounds, and D is $0.5*T_w$ plus the sum of the *deltim* for the two phases. The solution with the smallest C/D is selected. In effect this selects the event solution closest to the center of the area of overlap of the azimuth bounds.

4.3.4. Explanation

One of the defining attributes of an "expert system" is that it provide an explanation of the reasoning leading to its decisions. Expert system software techniques and languages (in this case, Lisp) facilitate the presentation of elaborate and complete explanation of the reasoning while all relevant data are resident in the program memory. However, in *IAS* interesting events happen at unpredictable and inconvenient times. Thus a scenario in which a seismologist must note the occurance of something interesting and ask the system to pause while he examines the reasoning is not practical. Instead, the choice is between two fundamentally different approaches: (1) obtain a complete explanation with typical expert system techniques by rerunning the expert system† for interesting data segments; or (2) cache enough information in the DBMS to provide an adequate explanation. The advantage of storing information in a DBMS are obvious; the disadvantage is that something important may be lost when forcing the information into this relatively rigid format.

Our *IAS* design decision was to satisfy the requirements for *explanation* exclusively through approach (2). *ASSESS* has no graphical or text displays beyond those used by programmers. All displays of *ASSESS* results and reasoning are based on *ASSESS* output cached in the DBMS. Included in this output is an "audit trail" stored in several DBMS tables. As discussed in Section 2.4, this audit trail serves two purposes. One is *explanation*, and the second is to provide a basis for *performance validation*, which is a cornerstone of the *IAS* approach to *knowledge acquisition* (see Section 4.7). The design of the audit trail is driven by the requirements for *performance validation*, and *explanation* requirements are secondary.

† Since it is always possible to rerun the expert system for any data segment and to see what it is doing (with debugging tools, if nothing else), the choice is really about how much effort to devote to the user interface to make this convenient.

4.3.4.1. *Audit Trail Organization*

ASSESS uses rule-based reasoning to interpret the data from *SigPro*. The objective is to maintain an audit trail that provides a basis for reconstructing the decision process, so it is not necessary to record every decision. Rules or groups of rules used to make important decisions are represented by "knowledge sources" (KS). These KS are segmented into seven distinct "KS classes," which follow closely the reasoning steps shown in Figure 4.2. These seven classes are:

- Signal Processing
  Knowledge used to declare a detection.
- Initial Phase Identification
  Knowledge used to identify phases as P, S, T, or N (Section 4.3.2.1).
- Detection Grouping
  Knowledge used to form the "initial detection grouping" (see Section 4.3.2.2).
- Phase Association
  Knowledge used to associate phases into event groups (Section 4.3.2.2).
- Final Phase Identification
  Knowledge used to assign the defining phase identifiers Pn, Pg, Sn, Lg, leading directly to a single-array location (Section 4.3.2.3).
- Event Grouping
  Knowledge used to group pairs of single-array locations that potentially represent the same event (Section 4.3.3).
- Network Location
  Knowledge used to form the final network location (Section 4.3.3).

These seven classes contain a total of 40 knowledge sources. The largest class is Final Phase Identification which contains 22. Some classes (Signal Processing, Detection Grouping, Event Grouping) contain only one KS. The motivation for the latter classes is not to provide information about decision process (it can usually be inferred), but to provide an audit record to be invalidated if the analyst effectively changes the decision made by *ASSESS* at that stage of the processing(see Section 4.7).

4.3.4.2. *Audit Trail Structure*

The audit trail is stored in the DBMS tables shown in Figure 4.4. *ASSESS* writes to the *detloc*, *audit* and *audvarbind* tables, while *kstemplate* and *paramdesc* are quasi-static lookup tables. Records in the *detloc* table link detected signals with event solutions (see Section 3.2). For each record in *detloc* there are seven records in *audit*, one for each KS class. Each of these audit records points to the KS which was used for the decision. Many KS use the values of parameters, and these values are written to the *audvarbind* table. That is, there is one *audvarbind* record for each parameter in the KS referenced by each *audit* record. For example, for each *detloc* record *ASSESS* writes 7 *audit* records and perhaps 28 *audvarbind* records (assuming an average of 4 parameters per KS).

The *audit* table is the key to performance validation, as discussed in Section 4.7. The other tables are primarily for explanation. The *kstemplate* table provides a text rendition of each KS. Definitions of the parameters that appear in the KS are stored in a readable form in *paramdesc*.

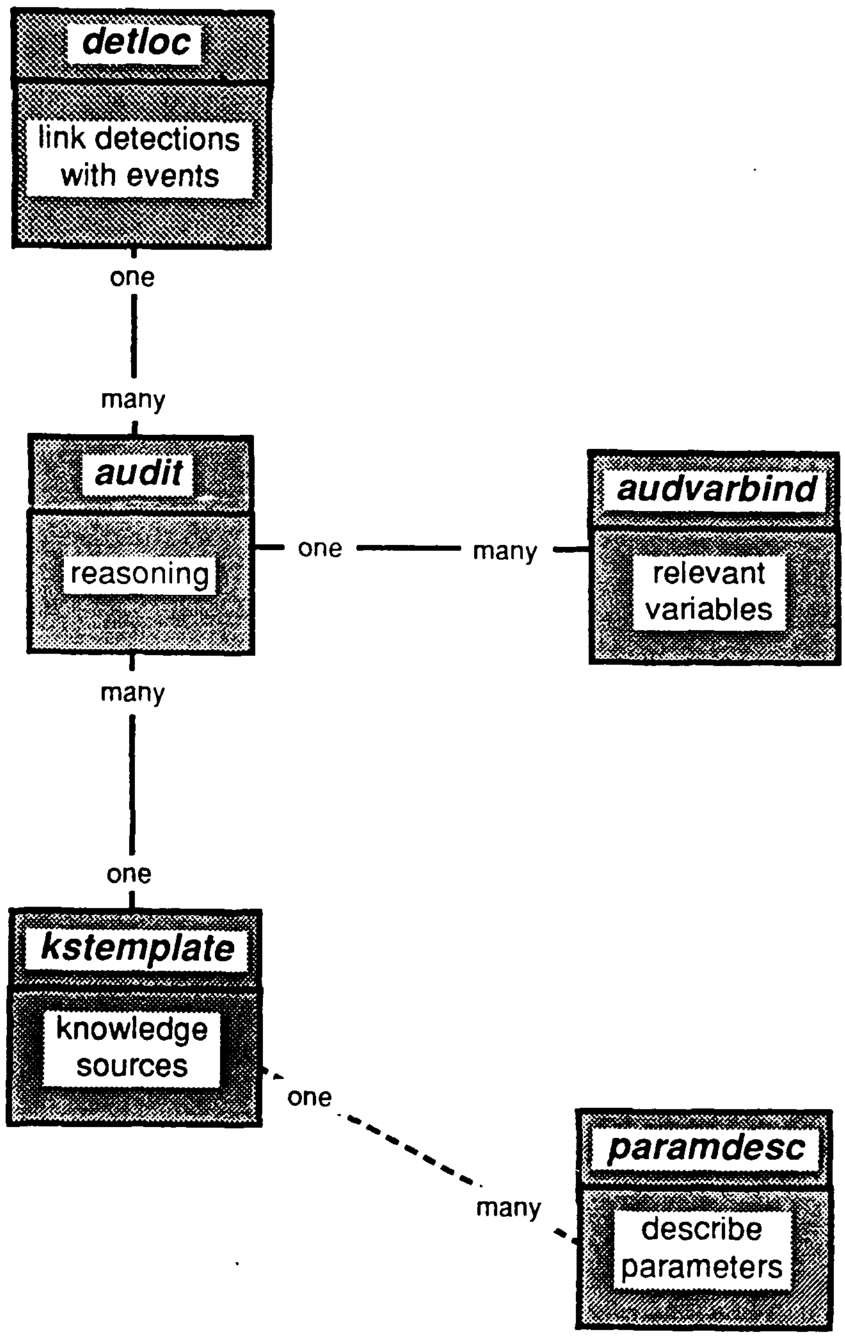


Figure 4.4. DBMS relations for storing *ASSESS* audit information. The dashed line indicates that an *ad hoc* linkage convenient for the ARS explanation facility is used rather than a conventional RDBMS linkage.

4.3.4.3. *Retrieving Explanation*

In *IAS* explanation is provided as a menu option in the Analyst Review Station (ARS) described in Section 4.6. For any event-detection pair (i.e., *detloc* record) the responsible knowledge source is obtained from *audit* for any one of the seven stages of the reasoning process. A human-readable version of this knowledge source is retrieved from *kstemplate*, and the value of any parameters appearing in this description is retrieved from *paramdesc*. Definition of the parameters is retrieved from *paramdesc* when requested.

4.3.5. Output of *ASSESS*

The output of *ASSESS* includes the following:

- An identification of every phase detected by *SigPro* as T, N, P, S, Pn, Pg, Sn, or Lg.
- An association of each defining phase (Pn, Pg, Sn, Lg) with an event location.
- A location for each event including a confidence ellipsoid.
- An audit trail containing a record of the major decision made during the interpretation process.

4.3.6. Magnitude Calculation

Since magnitude calculations require an event location, this process is done after the final location is determined. That is, after *ASSESS* and any location refinement processing (see Section 4.4) are finished. Also, if analyst review (Section 4.6) revises the location, the magnitude calculation must also be revised. In the Fall, 1989 operation of *IAS*, the magnitude calculations were not done as part of the automated near real-time processing, but as a post-process initiated after analyst review of the data was completed.

The magnitude in the *IAS* bulletins is computed from the amplitude of Lg. This is the peak amplitude of a filtered (2-4 Hz) incoherent beam (with no steering delays) of the available vertical channels in the A0, B, and C rings in the window between times defined by group velocities of 3.0 and 3.6 km/sec. The distance correction converting this amplitude to magnitude is taken from Båth *et al.* (1976). This magnitude is computed for each station which has any defining phase for the event (i.e., it need not have a detected and identified Lg phase). The network magnitude is simply the mean of the station magnitudes.

4.4. SCRIPT MATCHING AND ACQUISITION

The *ASSESS* module described in the previous section uses general and region-specific knowledge expressed in rules to associate detections with events. The travel-times and azimuth of these associated detections are then inverted for a location solution (Section 4.3.2.4). Specific characteristics of events previously seen in the vicinity of the estimated location are not considered directly in this process, and these can be very important for refining the location or identifying the nature of the event. This area-specific knowledge is represented in *IAS* by what are called *scripts*, and *script matching* is the process by which events are compared with these *scripts*.

The script concept was first developed in artificial intelligence research in automatic story understanding (Shanks and Abelson, 1977). Baumgardt(1987) suggested that this concept could be applied in seismology by using scripts to represent feature patterns for prototypical seismic events in a case-based reasoning system for event characterization. These seismic scripts would then be matched against features in the incoming data. An initial prototype implementing this concept was developed and described by Kandt *et al.* (1987) and Baumgardt (1987).

In *IAS* this concept is implemented in the *SAS* and *ScriptMatch* modules. The implementation is entirely due to the subcontractor team of Ensco and ISX (formerly Teknowledge Federal Systems). The description presented here is extracted from *IAS* project documents written by Doug Baumgardt and Sam Carter of Ensco and Paul Kegelmeyer of ISX.

The *script acquisition system* (*SAS*) analyzes the detections from a group of similar events to obtain a *script* that represents the robust characteristics distinguishing this group of events. In *script matching* the detections from an event are compared with a set of *scripts* to obtain a measure of the closeness-of-fit to each *script*. Simple rules are then applied to determine the confidence with which the current event can be said to be another instance of the group of events represented by the *script*. While not yet fully implemented, the concept is for this to provide a basis for refining the location by "joint epicenter" or "master event" methods (e.g., Douglas, 1967; Jordan and Sverdrup, 1981). It also provides information used for event identification (see Section 4.5) (e.g., the signals are so similar to those from previous events of a specific type that it is likely to be another instance of this type).

Effective *script matching* requires an adequate number of events to form statistically meaningful *scripts*. Since a significant period of routine operation is is required to acquire enough events, *script matching* is incorporated in the first operational version of *IAS* only for concept demonstration purposes. In this section we describe this first implementation of the *script matching* concept in the *ScriptMatch* and *SAS* software modules (Figure 3.1). Based on experience accumulated during the initial operational period, we expect to be able to define improved *scripts* which will become part of the routine operation.

4.4.1. Script Acquisition System (*SAS*)

The objective of *SAS* is to compute *script* that represent distinguishing patterns of features for significant groups of events (e.g., classification by specific location or by event type). There is a very large literature devoted to classification problems of this type.† Most techniques work best for large databases with unbiased sampling of the population considered. Seismic data are difficult because they are so biased. That is, there are many instances of some types of events,

† Some examples include Duda and Hart, 1973; Fisher and Langley, 1986; Quinlan, 1986. For a recent review with many references, see Weiss and Kapouleas, 1989.

and few or no instances of other important types of events. Also, the most robust classifiers of events in different areas (phase azimuths and the inter-phase time separation) provide a trivial classification at this stage of the processing (they have already been used by the rule-based location module). At this stage the need is for classification based on more subtle features that have not yet been considered. Some candidate features are relative amplitudes and azimuths of defining phases (or even coda detections), frequency content, polarization characteristics, phase velocity patterns, etc.

The *scripts* computed by *SAS* contain three sections:

- Header: Contains instance variables which describe information about the seismic event, including location, magnitude, and standard deviations of these source parameters, textual descriptions of the event (earthquakes, explosions, mine blast), source of the event information, and a list of the orids (unique identifiers of events in the DBMS) for the events which generated the *script*.
- Phase Description: This includes an instance for each phase expected in the script. Instance variables include the phase name, station id, number of occurrences of the phase which were found in the events that generated the script, and the prior probability of the phase occurrences. The latter is computed by dividing the number of phase occurrences by the total number of events used to produce the script. Also, a list of the arids (unique identifiers of detections in the DBMS) for the detections is included. The lists of orids and associated arids provides an audit trail of the data which produced the scripts.
- Feature List: Contains a list of features associated with the phase, their mean values, the observed standard deviations (*stdev*), and their match standard deviations (*mtchdev*).

SAS has access to all data output by the *SigPro* and *ASSESS* modules. In the initial implementation the features used to make *scripts* include *time, vel, seaz, stav, freq, ltav, STA(i),* and *LTA(i)*. The first three are defined in Section 4.3.1, and *freq* is the dominant frequency of the detection determined during the waveform analysis described in Section 4.2.3.1. In that section we also describe the computation of STA and LTA for six standard beams, and these are denoted by *STA(i)* and *LTA(i), i=1,..,6*. The *ltav* is the long-term average for the detecting beam; i.e., the beam on which *stav* is measured.

For the *scripts* the arrival times (*time*) are converted to relative arrival times (*reltim*) defined relative to the *time* for the earliest arriving phase associated with the event. The seven amplitudes are represented by relative values (*relsnr*) in decibels. These are computed from the ratio of the *stav* and STA(i) of each phase relative to the *ltav* and LTA(i) for the earliest arriving phase (i.e., with respect to the best available measure of the ambient noise).

In the current implementation *SAS* requires that the group of events to be represented by a *script* be selected interactively by a human analyst. Each event is represented by the "script features" *reltim, vel, seaz, freq*, and the seven *relsnr*, as described above. The *SAS* process aligns all phases in each event on the time of the first phase (i.e., *reltim* = *0*). A simple mean of the values of the "script features" is then computed for the defining phases (Pn, Pg, Sn, Lg) for each event in the group. If there are *n* events in the group, and a defining phase is present in only *m* events, the averaging is done over the these *m* events. This is represented by a "prior probability," which is the ratio *m/n*. This prior probability is used in the *script matcher* when calculating the overall confidence of a match. Along with the mean, *SAS* computes the sample standard deviation for each feature (*stdev*).

SAS computes *scripts* for events recorded by multiple arrays in the same way except that the *reltim* and *relsnr* are computed relative to the first associated phase (usually Pn from the nearest array). Thus, a multiarray *script* looks much the same as a single array *script* except that there may be multiple defining phases of the same type with different station names.

The *SAS* also includes a set of *a priori* estimates for the standard deviations, since the *stdev* are often unrepresentative, particularly for small samples of events. This *a priori* error estimate (called *mtchdev*) is part of the *script*, and so is available for use in the script matching process. Each feature in the *script* is assigned a weight between 0 and 1. The default value is 1, but the user can interactively reduce it to reduce the importance of this feature in subsequent script matching.

4.4.2. Script Matching (*ScriptMatch*)

The *ScriptMatch* module selects the best matching *scripts* from a list of candidate *scripts*. In most cases the candidate *scripts* are those for locations within the confidence ellipse for the event computed by *ASSESS*. The search can be expanded to include *scripts* for locations within some larger area that is a multiple of that confidence ellipse. The hypothesis formation can be done in two modes; forced and constrained. In the forced-match mode the phase identifications assigned by *ASSESS* are "force matched" against the same phases in the *script*, and the closest matching *script* are selected. In the constrained-match mode, all associated detections are matched against *scripts* without regard to the *ASSESS* phase identifications. In this mode *ScriptMatch* checks all possible P ($vel \geq 6$) and S ($vel < 6$) matches. Also calculated are feature, phase, and event (or script) match confidences.

Two kinds of features are defined in the scripts: Primary and Secondary. The Primary features are the ones used by *ASSESS* to identify and associate phases and include *time* and *seaz*. The Secondary features include *freq*, *vel* and the seven *relsnr* described in the previous section. Also, *ScriptMatch* has the capability to match amplitudes measured in spectral bins (using the spectrum for the phase output by *SigPro*). The spectral bins are identified in the *script*. An average rms amplitude is measured in these bins on both signal and noise spectra, and these spectral amplitudes are converted to *relsnr* values.

A standard deviation is also assigned to each feature. This can be *stdev*, the standard deviation of the population used to compute the *script* (appropriate for large populations), or it can be an assigned value called *mtchdev*. When only a single event is used to make the *script*, *mtchdev* is typically assigned as 10% of the feature value. For *reltim* a fixed value of 10 seconds is used in the current implementation.

An example of output of the *ScriptMatch* process is shown in Figure 4.4. In this case the best-matching *script* is one called "E6." It includes two phases, Pn and Lg, at NORESS. The details of the match for the primary and 2 secondary features for these two phases are shown in the bottom two panels. In these two panels "Script" is the value (a_s) of the feature stored in the *script*. "Event" is value (a_g) of the feature for the corresponding phase in the phase group. "Diff" is the difference ($a_g - a_s$) between the two. "Dev" is he sample standard deviation (s) of the feature (*stdev* or *mtchdev*). "Conf" is one minus the area under the normal distribution for the normal deviate, z, represented as $N(z,\sigma)$. The normal deviate (z) is:

$$z = \frac{a_g - a_s}{\sigma}$$

where σ is the standard deviation for the feature (*stdev* or *mtchdev*). High confidence indicates that "Diff" is small relative to the σ.

The *ScriptMatch* event confidence (65.7% for the example in the figure) is derived from the feature and phase confidences. The feature confidence is the "Conf" described above. In the current implementation, the phase confidence is the simple average of the feature confidences, and the event confidence is the simple average of the phase confidences. For the latter each phase confidence is weighted by the prior probabilities stored in the *script*, thus weighting this phase by the probability that it will be observed. For the example in Figure 4.5, the prior probability is unity for each phase. The "primary confidence" listed for the event is the simple average of the "conf" for the primary features for the two phases, and the "secondary confidence" is the simple average of the "conf" for secondary features.

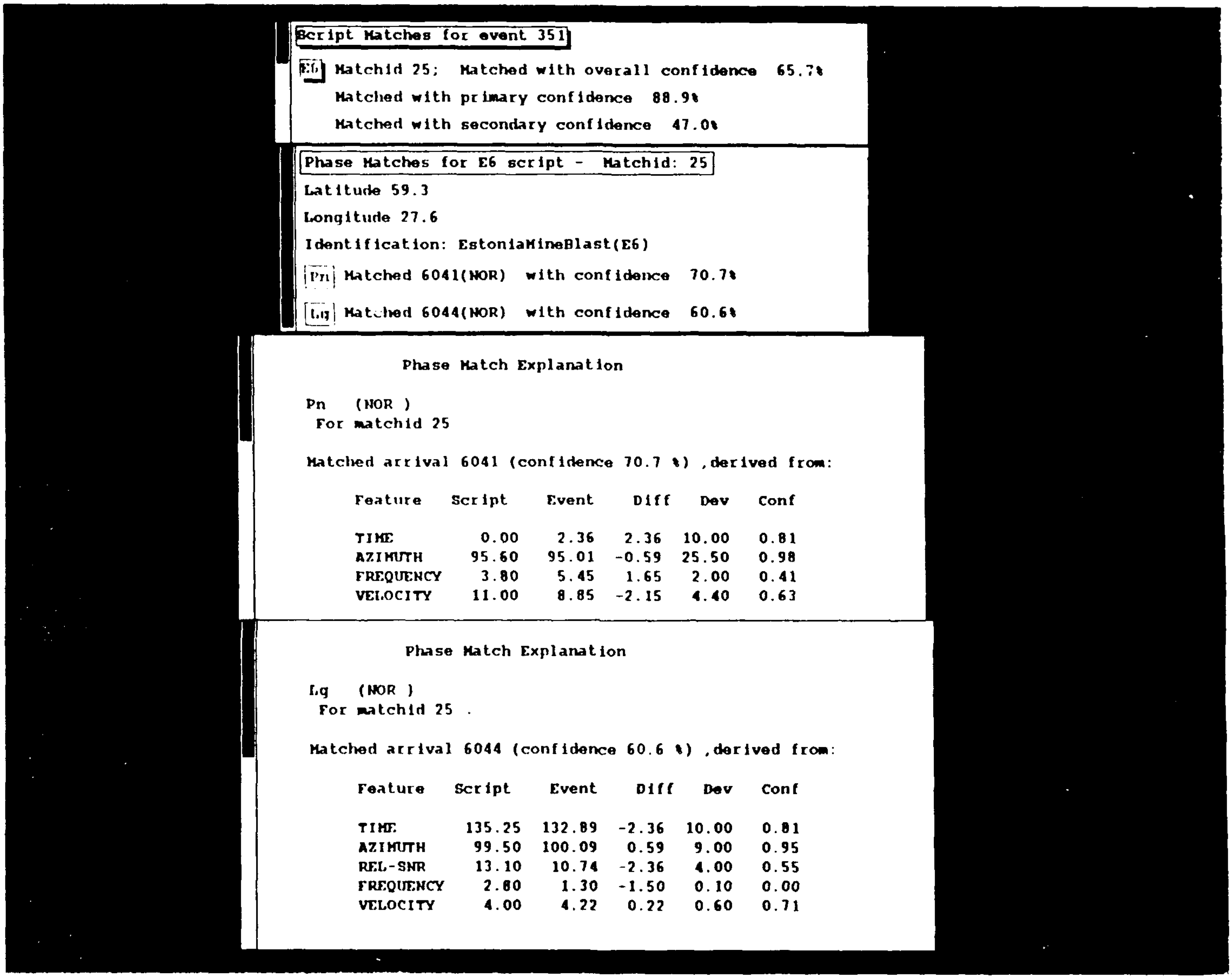


Figure 4.5. The output of tthe *ScriptMatch* process includes three different displays. The best-matching scripts (up to three) are listed in the top panel with the confidence estimates. The second panel shows the confidence of the match for each phase in the script, and the bottom two panels show the match for several features for each phase.

4.5. EVENT IDENTIFICATION

In the initial implementation of *IAS*, the event identification module (*EventId*) is a post-processor started manually (or on a schedule) for events meeting some preset criteria (e.g., all events above magnitude 2 within the Soviet Union). Events are identified within five classes:

EX	Almost certainly an industrial explosion
UNK-EX	Explosion-like
UNK	Unidentified
UNK-EQ	Earthquake-like
EQ	Almost certainly an earthquake

This identification is based on the event location and results from three event characterization processes: *ScriptMatch*, *MERSY*, and *Sratio*. The *script matching* was described in Section 4.4. The *MERSY* (Multiple-Event Recognition System) process seeks evidence of "ripple-firing" which is uniquely characteristic of industrial explosions. The *Sratio* process estimates S/P spectral ratios, which can be uniquely characteristic of earthquakes. In this section we describe the implementation of the latter two processes. We then describe how the event characterization information is fused to obtain the overall event identification.

4.5.1. Multiple-Event Recognition System (*MERSY*)

The *MERSY* module was developed by Ensco, Inc., under a subcontract to SAIC. The technical basis is presented by Baumgardt and Ziegler (1988). A functional description of the program, including examples, appears in Baumgardt and Ziegler (1989). The description here is is an edited version of material in that report.

The input to *MERSY* includes the output of *ASSESS* (Section 4.3.5) and the output of *SigPro* (Section 4.2.4), most notably the spectrum of every detected signal and a preceding noise segment which is used for computing the cepstrum for that signal. *MERSY* then computes two kinds of cepstra and seeks cepstral peaks that persist at the same quefrency for all detected phases. Rule-based reasoning is then applied to characterize the strength of the evidence that the event includes closely-spaced (in time) multiple arrivals characteristic of a ripple-fired industrial explosion.†

Figure 4.6 shows the data flow within the *MERSY* and the major subprocesses. Two cepstra are computed, one (FFTCEPST) by a straightforward Fourier transform of the log spectra, and the second (MAXENT) by a maximum entropy method. FFTCEPST reads the spectra and computes the Fourier cepstra as described by Baumgardt and Ziegler (1988). As noted by these authors, truncation of the spectra at Nyquist can produce distorted and false modulation peaks, particularly if the truncation occurs in the middle of one of the spectral modulation cycles. The maximum entropy method extrapolates the spectrum to frequencies beyond Nyquist using a predictive filter in the frequency domain, and so should eliminate these spurious peaks and produce much sharper main peaks.

These two cepstra are computed for all the phases associated with the event. If only one array has phases associated with the event the peaks and cepstral statistics are extracted from the

† Baumgardt and Ziegler (1989) suggest that underwater explosions have similar cepstral characteristics, but more data are needed to increase confidence in this conclusion.

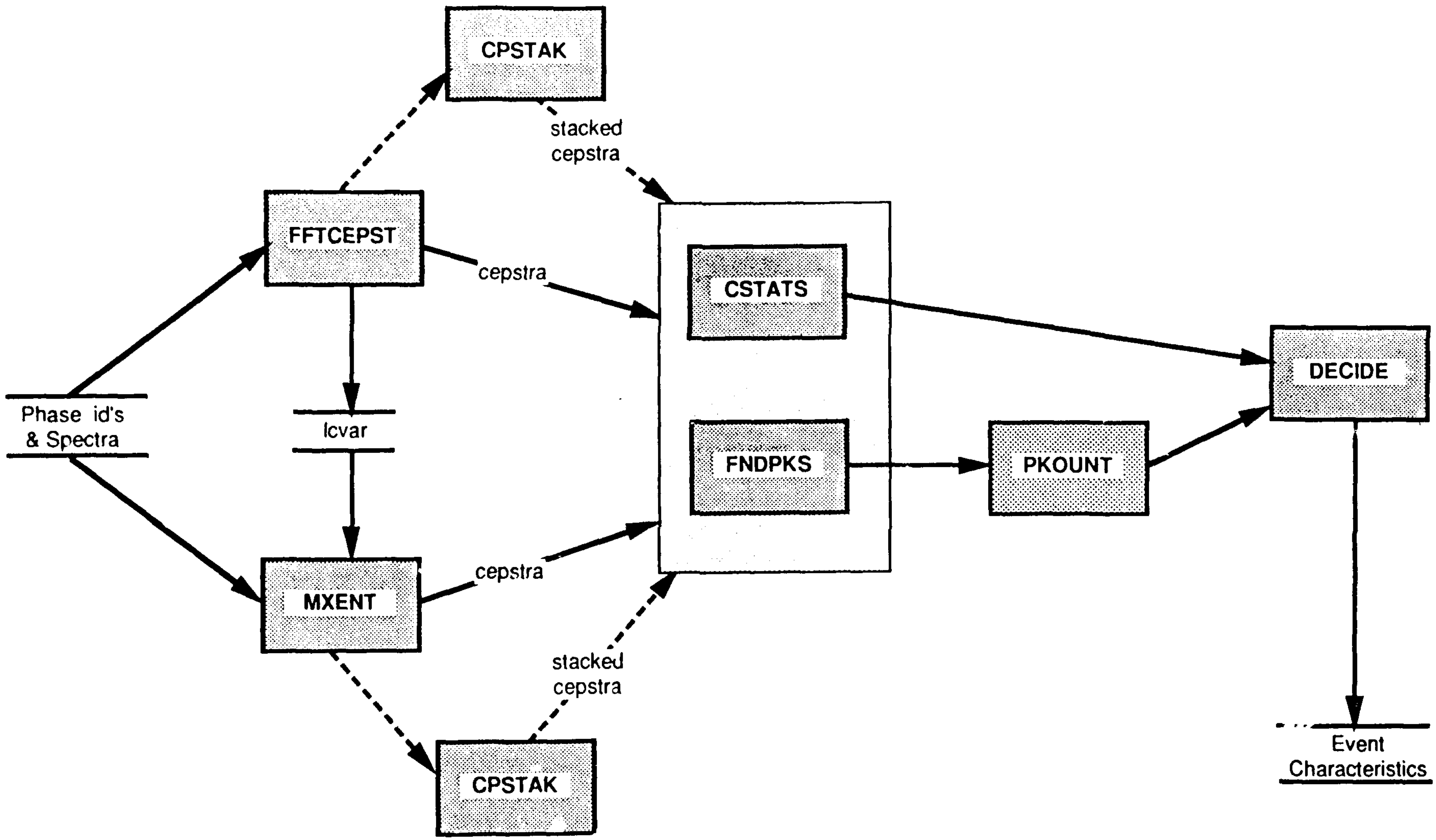


Figure 4.6. The data flow among the major subprocesses of *MERSY* is shown. The associated phases at each arrray follow the path indicated by solid lines. When there are data from more than one array, the individual phase spectra are stacked, and path indicated by dashed lines is followed instead.

(CPSTAK), and FNDPKS, CSTATS, and PKOUNT subprocesses are applied to these stacked cepstra. The final process (DECIDE) analyzes the pattern of cepstral peaks and their frequencies to determine whether the event is a multiple event and the confidence in that decision. For apparent multiple events the delay time(s) and number of events are estimated. These subprocesses are described in more detail in subsequent subsections.

4.5.1.1. *Fourier Cepstra (FFTCEPST)*

This subprocess reads the Fourier cepstra computed by *SigPro* for each associated phase and computes the cepstra as follows. The instrument response is removed by spectral division, and the log-rms signal-to-noise ratio is computed (converted to DB and called *snrdb*). The logarithm of each spectral density is then computed to whiten the spectrum. The quadratic trend is removed from a low frequency cutoff of 1.875 Hz to Nyquist (20 Hz). This quadratic trend removal eliminates false cepstral peaks due to the high frequency rolloff of the spectrum. The low frequency cutoff suppresses the false cepstral peaks due to the instrument response removal. This whitened log-amplitude spectrum is used for both the Fourier cepstrum and the maximum-entropy cepstrum described in the next subsection. The Fourier cepstrum is the real part of an FFT of the log-amplitude spectrum after reflection about the Nyquist frequency.

4.5.1.2. *Maximum Entropy Cepstra (MXENT)*

This subprocess computes a cepstrum by treating the amplitude spectrum as a time-series using the Burg (1967) maximum-entropy power spectrum method implemented with the algorithm described by Anderson (1974). The algorithm requires selection of the number m of coefficients a_{mn} to be included in the predictive filter for n frequency points. This m depends on the complexity of the cepstrum, which is estimated from the logarithm of the Fourier cepstral variance, *lcvar* (the calculation of variance is described in Section 4.5.1.4). The following rules are used:

$$lcvar \leq -4.7 \rightarrow m = 60$$

$$lcvar > -4.7 \text{ and } lcvar \leq -4.5 \rightarrow m = 80$$

$$lcvar > -4.5 \text{ and } lcvar \leq -4.3 \rightarrow m = 90$$

$$lcvar \geq -4.3 \rightarrow m = 100$$

4.5.1.3. *Cepstral Peak Analysis (FNDPKS)*

This subprocess scans cepstra to find peaks. Each point where the slope changes sign from positive to negative (*pk*) is a possible peak. The nearest points on either side of *pk* where the slope changes sign from negative to positive are found (*tr*1 and *tr*2). Using the maximum value in the cepstrum (*maxcep*), a *pk* is declared a peak if

$$pk - \left[\frac{|tr2 - tr1|}{2}\right] \geq 0.2\ maxcep.$$

4.5.1.4. *Spectral/Cepstral Statistics (CSTATS)*

This subprocess computes the *variance*, *skewness*, and *kurtosis* of the spectra and cepstra.† The *variance* is a measure of the spectral or cepstral "width" or "variability" around the mean value. If x_j represents the jth spectral or cepstral value and $\bar{x}$ the mean value, then the variance or *second moment* is:

$$Var(x_1......x_N) = \frac{1}{N-1}\sum_{j=1}^{N}(x_j - \bar{x})^2,$$

where N is the number of points in the spectrum or cepstrum.

The *skewness* characterizes the degree of asymmetry of a function about its mean value. It is represented as the *third moment* expressed as

$$Skew(x_1........x_N) = \frac{1}{N}\sum_{j=1}^{N}\left\{\frac{x_j - \bar{x}}{\sigma}\right\}^3,$$

where $\sigma = \sigma(x_1 \cdots x_n)$ is the *standard deviation* of the spectral or cepstral distribution. An estimate of the standard deviation is

$$\sigma(x_1........x_N) = \sqrt{Var(x_1 \cdots x_N)}.$$

The *kurtosis* gives a measure of the "peakedness" or "flatness" of the spectrum or cepstrum relative to a normal distribution function. This feature, also known as the *fourth moment*, is expressed as

$$Kurt(x_1........x_N) = \left\{\frac{1}{N}\sum_{j=1}^{N}\left[\frac{x_j - \bar{x}}{\sigma}\right]^4\right\} - 3.$$

The *Kurt* is zero when the spectrum or cepstrum is normally distributed.

4.5.1.5. *Peak Counting (PKOUNT)*

This subprocess counts significant peaks that are consistent in the sense that they occur at the within one quefrency bin in two or more cepstra within the group under consideration. For data from one array cepstra for all associated phases are examined. When the event has data from both arrays, the stacked spectra from each are examined. Peaks are considered to be significant if they have a high amplitude and are not present in the noise cepstrum for the noise segment prior to the earliest phase associated with the event (the best available estimate of the ambient noise). If pks_i and pkn_i are the signal and noise peaks, for quefrency bin i, pks_i is significant if

$$pks_i \geq th_s \text{ and } (pkn_i < th_n \text{ or } pks_i > 3*pkn_i),$$

The lack of a noise peak in the ith cepstral bin satisfies the condition $pkn_i < th_n$. For Fourier cepstra, $th_s = th_n = 0.032$, and for maximum entropy cepstra, $th_s = th_n = .001$.

† While all three of these statistics are computed and archived in the DBMS, only *variance* is used in subsequent steps in the current implementation of *MERSY*.

4.5.1.6. *Source Multiplicity Determination (DECIDE)*

This subprocess applies a set of rules to the logarithm of the cepstral variance (*lcvar*) of the last phase, the number of Fourier cepstral peaks (*nfp*), and the number of maximum-entropy cepstral peaks (*nmep*) to provide an independent classification of the event as a likely mine or underwater explosion (exp) or a likely earthquakes (*equ*). The rules are:

$$IF\ nfp > 0 \text{ and } lcvar > lcvarth \rightarrow exp;$$

$$IF\ nfp > 0 \text{ and } lcvar < lcvarth \text{ and } nmep = 0 \rightarrow equ;$$

$$IF\ nfp = 0 \text{ and } lcvar > lcvarth \text{ and } nmep > 0 \rightarrow exp;$$

$$IF\ nfp = 0 \text{ and } lcvar < lcvarth \rightarrow equ;$$

$$IF\ nfp > 0 \text{ and } lcvar < lcvarth \text{ and } nmep > 0 \rightarrow exp;$$

$$IF\ nfp = 0 \text{ and } lcvar > lcvarth \text{ and } nmep = 0 \rightarrow equ.$$

The log cepstral variance threshold, *lvarth*, is set to -4.5.

The independent classification provided by the *DECIDE* subprocess is not used in *IAS*. Instead, the event characteristics found by *MERSY* are used in the *EventId* process described in Section 4.5.3.

4.5.1.7. *Event Characteristics*

The *MERSY* output used by *EventId* includes the *snrdb* computed by *FFTCEPST*, the logarithm of the Fourier cepstral variance (*lcvar*) computed by *CSTATS*, and kurtosis of the Fourier cepstrum (*ckur*) computed by *CSTATS*. Another important attribute writen by *MERSY* is the peak type, *ptyp*, which is defined to be:

FC-ARY If there are consistent peaks in the Fourier cepstra across two or more arrays.

MC-ARY If there are consistent peaks in the maximum entropy cepstra across two or more arrays.

FC-PHS If there are consistent peaks in the Fourier cepstra across two or more phases for one array.

MC-PHS If there are consistent peaks in the maximum entropy cepstra across two or more phases for one array.

FC-NOI If there are consistent noise peaks in the Fourier cepstra

MC-NOI If there are consistent noise peaks in the maximum entropy cepstra.

4.5.2. S/P Spectral Ratio (*Sratio*)

The *Sratio* module computes the ratio of the apparent source excitation of *Lg* and *Pn* phases using the path corrections of *Sereno et al.* (1988) applied to *Pn* and *Lg* spectra. These path-corrected spectra are inverted for the long-period source level and corner frequency (assuming a source model with frequency-squared decay above the corner frequency). The ratio of the *Lg* and *Pn* source levels is computed for each station and averaged across the network. This average ratio is used to identify the event by comparing to the source excitation ratios for previous events of known source type. This method is described in more detail in the following subsections.

4.5.2.1. *Computation of S/P Source Level*

The input to *Sratio* includes the output of *ASSESS* (Section 4.3.5) and the spectra computed by *SigPro* (Section 4.2.4). The *Pn* and *Lg* SNR spectra are computed using the pre-*Pn* noise spectrum, and a 3-Hz running mean filter is applied to these SNR amplitude spectra. The path corrections are applied to a frequency band over which the smoothed SNR spectrum is ≥ 1.5, but no greater than the band used to determine the path corrections (1–15 Hz for *Pn* and 1–7 Hz for *Lg*). These smoothed, band-limited spectra are corrected for the instrument response and converted to physical units (nm-s).

The *Pn* and *Lg* path corrections of *Sereno et al.* (1988) include geometric spreading and a *Q*-operator determined by inverting spectra computed for fixed 5-s time windows (i.e., the *SigPro* spectra). The path-corrected spectra, $S(f)$, are expressed in terms of the instrument-corrected amplitude spectra, $A(f)$, as:

$$S(f) = A(f) r_0 \left[\frac{r}{r_0}\right]^m \exp\left[\frac{\pi f t}{Q(f)}\right]$$

where r_0 is the transition distance from spherical spreading to spreading rate m, r is epicentral distance, t is travel time, and $Q(f)$ has a power-law frequency dependence given by $Q_0 f^{\eta}$. The path parameters for *Lg* are: $r_0 = 100$, $m = 0.5$ (cylindrical spreading), $Q_0 = 350$, and $\eta = 0.41$. The path parameters for *Pn* are: $r_0 = 1$, $m = 1.3$, $Q_0 = 300$, and $\eta = 0.49$.

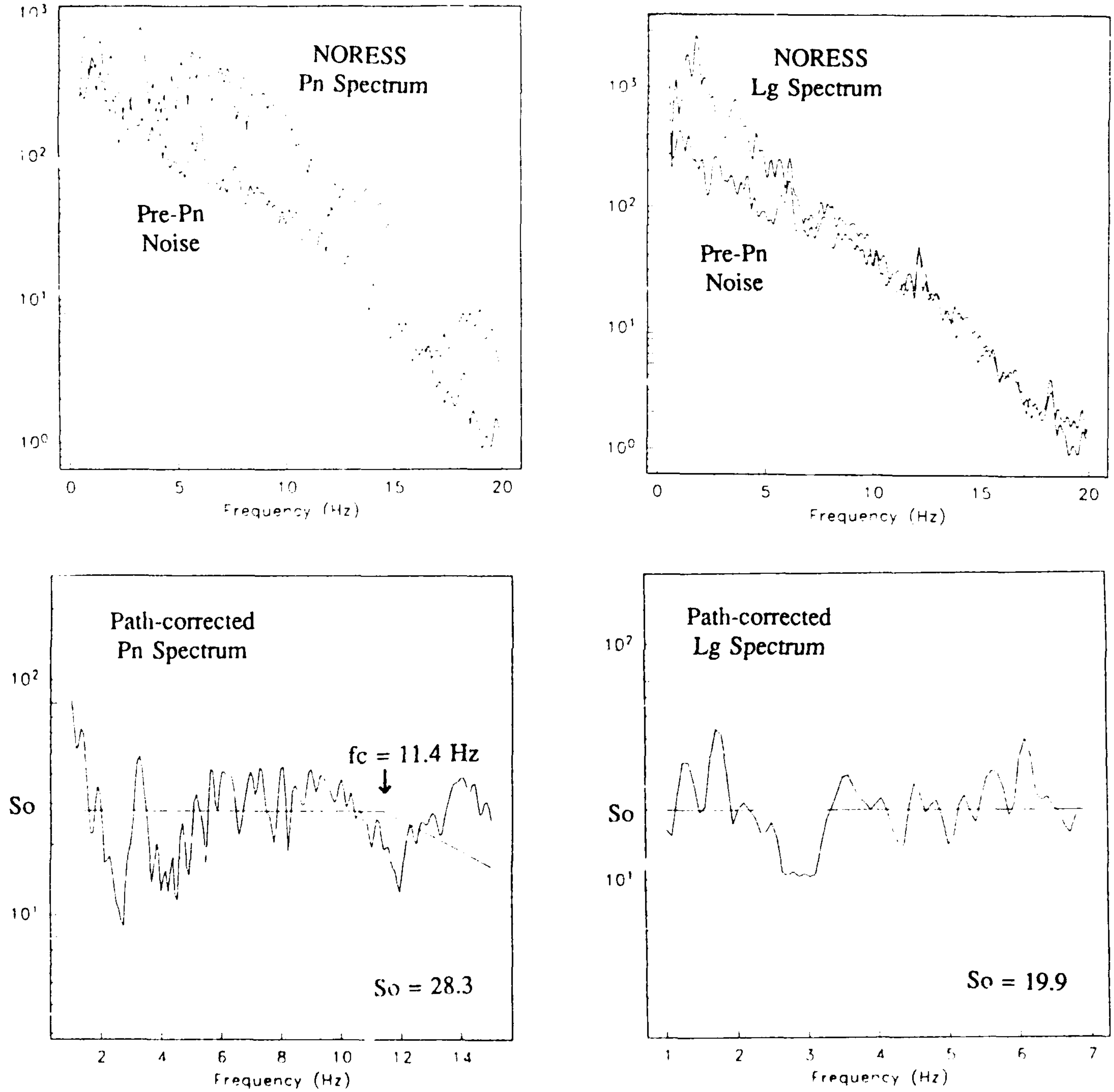
The source is assumed to have frequency-squared decay above the corner frequency, and the path-corrected spectra are inverted for the long-period level (S_0) and the corner frequency (f_c) using iterative damped least squares. The data variance (the variance of the fit of the source model to the path-corrected spectra) and the variance of log S_0 (parameter variance) are computed.

An example of the path corrections and source parameter inversion is shown in Figure 4.7. This figure shows the spectra recorded at NORESS from a mine blast in Estonia (epicentral distance is 930 km) and the same spectra after path correction over the frequency band used to determine the NORESS path corrections. The derived *Pn* and *Lg* source spectra are superimposed on the path-corrected spectra, and the long-period levels are 28.3 for *Pn* and 19.9 for *Lg*. The corner frequency (estimated from *Pn*) is 11.4 Hz. The NORESS *Lg/Pn* source excitation ratio is 0.7 for this event.

4.5.2.2. *Earthquake Classification with Sratio*

The ratio $S_0(Lg)/S_0(Pn)$ is computed for each station. The network-average ratio is calculated from the individual ratios at each station weighted by the standard deviation of the log S_0 estimate. Event classification is based on comparison of this ratio with values 122 events with known classification (*Sereno et al.*, 1988). In Figure 4.8 the *Lg/Pn* source excitation ratios

M_L 2.7 Mine Blast, 930 km from NORESS



So (Lg)/So (Pn) = 0.70
Earthquake Rating = 0

Figure 4.7. Example of observed and path-corrected spectra for an M_L 2.7. mine blast in Estonia recorded at NORESS. The path-corrected spectra are plotted over the frequency band used to determine the NORESS path corrections (*Sereno et al.*, 1988). The derived *Pn* and *Lg* source spectra are superimposed on the path-corrected spectra.

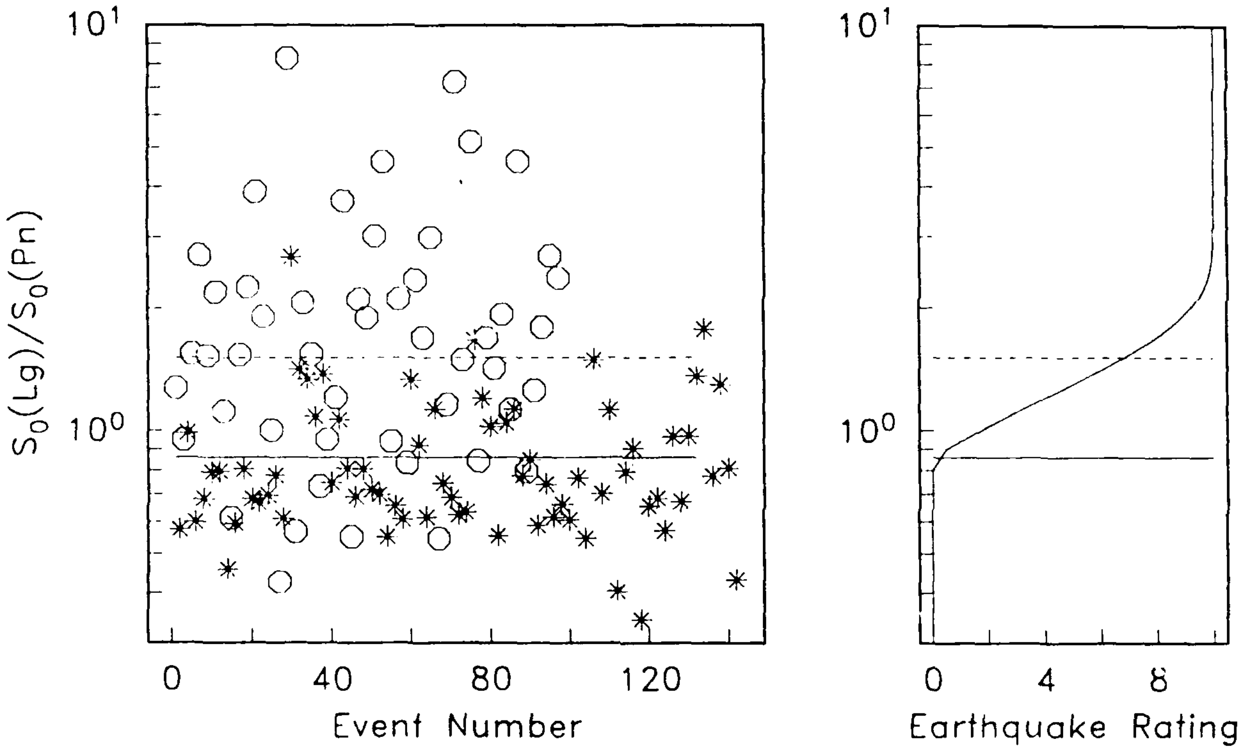


Figure 4.8. Lg/Pn long-period source excitation ratios from 132 events with known classification. Explosions are plotted as asterisks and earthquakes as open circles. The mean and standard deviation of the explosion ratio are indicated by horizontal lines. The earthquake rating is plotted in the right panel as a function of *Lg/Pn* source excitation ratio.

from these events are shown with explosions plotted as asterisks and earthquakes as open circles. Clearly, a low value of this ratio is inconclusive, whereas high values indicate the event is probably an earthquake.

An earthquake-classification rating is computed for a new event as indicated at the right in Figure 4.7. We assume that the *Lg/Pn* source excitation ratio for the 71 explosions is normally distributed. As shown in Figure 4.7, the mean value is 0.86, and the standard deviation is 0.65. For source ratios less than or equal to the mean value for the explosion data set, the earthquake-classification rating is set to zero, indicating an inconclusive classification. Above the mean the earthquake-classification rating is computed from the normal distribution over the range from 0 to 10, with 10 indicating the highest probability that the event is an earthquake.

4.5.3. Information Fusion to Identify Events

Event identification (classification) is done in the *EventId* process. In the current *IAS* implementation this process includes a rule-based fusion of information from:

- Location
- Script matching (from *ScriptMatch*, Section 4.4)
- Evidence of ripple-firing (from *MERSY*, Section 4.5.1)
- S/P spectral ratios (from *Sratio*, Section 4.5.2)

Each provides an independent classification into one of the five classes listed at the beginning of Section 4.5 (EX, UNK-EX, UNK, UNK-EQ, EQ). These independent classifications are then combined by a weighted voting scheme to obtain an overall event classification.†

The event characteristics used for the classification include:

S1,S2,S3 The three scripts (in order) with highest confidence of match.

C1,C2,C3 The combined primary and secondary confidences for the three highest confidence scripts.

P(cls) The proportion of the three matching *scripts* that in a particular class (*cls*). For example, if 2 are from mines (*mn*), and 1 is from an underwater explosion (*uwe*), *P(mn)* = 0.66 and *P(uwe)* = 0.33. Other classes include nuclear explosions (*nuc*) and earthquakes (*eq*).

erat The "earthquake rating" determined from $S_0(Lg)/S_0(Pn)$ and defined in Figure 4.8 (Section 4.5.2.2).

Also used are the *ptyp*, *snrdb*, *cvar*, and *ckur* output by *MERSY* (Section 4.5.1.7). The classification is quantified by the following:

conf Indicates the confidence in the classification by one of the four independent methods.

wt Indicates the the weighting applied to this particular confidence when fusing the classification from the four methods to obtain an overall event classification.

† The concept, the rules for *MERSY* and *ScriptMatch*, and the weighted voting scheme are due to Doug Baumgardt, Ensco, Corp. The rules for *Sratio* are due to Tom Sereno, SAIC.

4.5.3.1. *Event Classification by Independent Methods*

The rules used to classify events by the four independent methods are as follows:

<u>Location</u>

EQ	with *conf* = *0.9* and *wt* = *0.8* If the area enclosed by the confidence ellipse is in the deep ocean (beyond the continental shelf)
UNK-EQ	with *conf* = *0.7* and *wt* = *0.8* If the area enclosed by the confidence ellipse is offshore, but the location is on the continental shelf
UNK-EX	with *conf* = *0.25* and *wt* = *0.9* If *max*[*Ci*] > *0.5* and *P(mn)* = *1.0*
UNK	with *conf* = *0.0* If none of the other rules for identification by location are satisfied.

<u>Script Matching</u>

EQ	with *conf* = *0.9* and *wt* = *0.8* If *P(eq)* = *1.0* and *max*[*C1,C2,C3*] ≥ *0.8* or *S1* represents earthquakes with *C1* ≥ *0.9* and *P(eq)* < *1.0*
UNK-EQ	with *conf* = *0.75* and *wt* = *0.8* If *P(eq)* = *1.0* and *0.5* < *max*[*C1,C2,C3*] < *0.8* or *S1* represents earthquakes with *0.8* < *C1* < *0.9* and *P(eq)* < *1.0*
UNK-EQ	with *conf* = *0.25* and *wt* = *0.8* If *P(eq)* = *1.0* and *max*[*C1,C2,C3*] < *0.5* or *S1* represents mining explosions with *C1* < *0.6* and *P(eq)* < *1.0*
UNK-EX	with *conf* = *0.25* and *wt* = *0.8* If *P(mn)* = *1.0* and *max*[*C1,C2,C3*] < *0.5* or *S1* represents *cls* = *mn*, *nuc*, or *uwe* with *C1* < *0.6*
UNK-EX	with *conf* = *0.5* and *wt* = *0.8* If *P(mn)* = *1.0* and *0.5* < *max*[*C1,C2,C3*] < *0.8* or *S1* represents *cls* = *mn*, *nuc*, or *uwe* with *0.6* < *C1* < *0.9*, and *P(mn)* < *1.0*
EX	with *conf* = *0.9* and *wt* = *0.85* If *P(mn)* = *1.0* and *max*[*C1,C2,C3*] ≥ *0.8* or *S1* represents *cls* = *mn*, *nuc*, or *uwe* with *C1* ≥ *0.9*, and *P(mn)* < *1.0*
UNK	with *conf* = *0.0* If none of the other rules for identification by script matching are satisfied.

<u>*MERSY*</u>

UNK-EX	with *conf* = *0.25* and *wt* = *0.75* If *ckur* > *11.69* * *cvar* + *38* and *ckur* < *30* for any of the stacked single array or multiple array cepstra which have *snrdb* < *1.0*
UNK-EX	with *conf* = *0.5* and *wt* = *0.75* If *ckur* > *11.69* * *cvar* + *38* and *ckur* ≥ *30* for any of the stacked single array or multiple array cepstra which have *snrdb* < *1.0*

UNK-EX with *conf* = *0.7* and *wt* = *0.75*
If $ckur > 11.69 * cvar + 38$ and $ckur < 30$ for any of the stacked single array or multiple array cepstra which have $snrdb \geq 1.0$

EX with *conf* = *0.9* and *wt* = *0.9*
If $ckur > 11.69 * cvar + 38$ and $ckur \geq 30$ for any of the stacked single array or multiple array cepstra which have $snrdb \geq 1.0$

EX with *conf* = *0.9* and *wt* = *0.95*
If two of the following conditions are satisfied for any of the stacked single array or multiple array cepstra: *ptyp = FC-PHS, ptyp = MC-PHS*, $ckur > 11.69 * cvar + 38$

EX with *conf* = *0.95* and *wt* = *0.95*
If two of the following conditions are satisfied for any of the stacked single array or multiple array cepstra: *ptyp = FC-ARY, ptyp = MC-ARY*, $ckur > 11.69 * cvar + 38$

UNK with *conf* = *0.0*
If none of the other rules for identification by cepstral characteristics are satisfied.

<u>*Sratio*</u>

EQ with *conf* = *0.9* and *wt* = *0.9*
If $erat \geq 8$

UNK-EQ with *conf* = *erat/10* and *wt* = *0.8*
If $2 < erat < 8$

UNK with *conf* = *0.0*
If $erat \leq 2$

4.5.3.2. *Overall Event Classification*

A simple weighted voting scheme is used to combine the four independent classifications to obtain an overall event classification. The four independent classifications are represented by *conf(i)* and *wt(i)*, with *i*=1,2,3,4. When the classification is EX, UNK-EX, or UNK,

$$conf(i) = conf.$$

When the classification is EQ or UNK-EQ,

$$conf(i) = -conf.$$

The overall classification is determined from

$$cest = \sum_{i=1}^{4} conf(i) * wt(i)$$

The values of *conf(i)*wt(i)* that occur for the rules used in the current implementation are tabulated below:

	Location	*ScriptMatch*	*MERSY*	*Sratio*
EQ	-0.72	-0.72	0	-0.81
UNK-EQ	-0.52	-0.2, -0.6	0	-0.64 ... -0.16
UNK	0	0	0	0
UNK-EX	0.23	0.2, 0.4	0.19 .. 0.53	
EX	0	0.77	0.81 .. 0.90	0

Events are identified by summing the approprite values to compute *cest*, then applying the following rules:

EQ	with *conf* = -*cest*/2.25 If *cest* ≤ -2.0
UNK-EQ	with *conf* = -*cest*/2.25 If -2.0 < *cest* ≤ -0.6
UNK-EX	with *conf* = *cest*/2.25 If 0.6 < *cest* < 1.55
EX	with *conf* = *cest*/2.25 If *cest* ≥ 1.55
UNK	with *conf* = -*cest*/2.25 If -0.6 < *cest* < 0.6

With these rules, *Sratio* has no role in identifying an explosion, and *MERSY* has no role in identifying an earthquake. The conditions for identifying an event as an explosion (EX) include:

- *MERSY* = EX, *ScriptMatch* = EX , *Location* = UNK-EX
- *MERSY* = EX, *ScriptMatch* = EX , *Location* = UNK

Similarly, the conditions for identifying an event as an earthquake (EQ) are:

- *Sratio* = EX, *ScriptMatch* = EX , *Location* = EX
- *Sratio* =EX, *ScriptMatch* = EX , *Location* = UNK-EX
- *Sratio* = EX, *ScriptMatch* = UNK-EX, *Location* = EX

Other combinations classify events as UNK-EX, UNK-EQ, and UNK, with the attached *conf* (ranging from minimum of -1.0 for class EQ to a maximum of 0.84 for class EX) providing a rough indication of the strength of the evidence that an event is an explosion or earthquake.

These event classification rules are an *ad hoc* representation of current knowledge for identifying events with regional array data. Much more empirical work is required to develop and test rules that provide truly effective event classification. Also needed is a more rigorous seismological and statistical basis for the rules in each method and the fusion of evidence from them. The *IAS* provides for the first time an operational system capable of collecting the data for a thorough investigation of these important issues.

4.6. ANALYST REVIEW

The important processes for analyst review (Figure 3.1) include *ARS* (Analyst Review Station), *map*, and *IVAS*. *ARS* provides the interactive display and editing tools to review, explain (Section 4.3.4), and correct the solutions. It is tightly integrated with the *map* process for geographical displays. *IVAS* is a special-purpose system (from International Imaging Systems, Inc.) for display and manipulation of imagery. In *IAS* the *IVAS* is used primarily for satellite images from SPOT Image Corporation, and this capability is also integrated with *ARS*.

In this section the emphasis is on *ARS* interaction with the DBMS, since analyst validation of *ASSESS* solutions is an important part of knowledge acquisition (Section 4.7). The user-interface and functions of the graphics-intensive interactive processes are described in the user-documentation, † particularly the **Analyst Review Station Tutorial**, the **Analyst Review Station Reference Manual**, and the **Map Tutorial**. The *IVAS* has extensive documentation from the vendor describing its functions, and examples of the imagery used in *IAS* are given in Fox (1989).

A typical screen viewed by the analyst is shown in Figure 4.9. A particular event has been selected for review and correction. In this example *ASSESS* has made a minor error in the identification of the Sn arrival at NORESS. Using *ARS* tools, the analyst can interchange the identity of the two closely-spaced NORESS S phases, since the second appears to be at the actual Sn arrival time. Since the new Sn arrival time is close to the expected Sn arrival time for original location solution, we know that this change will not move the location very much.

The analyst usually expands the trace to examine the onset time estimated by the automatic solution, and adjustments in this are very common (the onset time method used by *SigPro* requires improvement since the analyst often disagrees with it). The analyst can also add, delete, associate and disassociate phases. In the example shown no Lg was detected automatically at ARCESS, and the analyst could add it (though this poorly-defined phase should not be picked).

The *ASSESS* solutions are written to the *detection* (Version 2.8 DBMS), *detloc* (Version 2.8 DBMS), and *loc* (Appendix A) relations, with the attribute *loc.status*‡ written as "expert." The analyst can choose to validate, invalidate, or change the *ASSESS* solution. Upon validation the *loc.status* attribute is changed to "valid." If the solution is invalidated or changed, *loc.status* is changed to "invalid." The new solution (or a null solution if the *ASSESS* solution is invalidated) is written to the *loc* relation, with links between the *ASSESS* and analyst *loc* tuples for this "event" maintained via the *locnorid* and *locporid* relations (Appendix A). All detections that have been altered are written to the *detection* relation, with the *detloc* relation providing the links between each *loc* tuple and its associated *detection* tuples. When a detection is altered (renamed, retimed, etc.), the DBMS maintains a link between the old and new (analyst) *detection* tuples by the *detloc.pdlid* and *detloc.ndlid* attributes. When the analyst marks a solution "invalid," all defining phases (Pn, Sn, etc.) are changed to the corresponding undefining phases (P, S) and linked to the corresponding null tuple in *loc*. When the analyst deletes a phase, a *detloc* tuple is written with *detloc.phase* = "glitch," and when the analyst adds a phase, a new *detection* tuple is written with *detloc.pdlid* = "null" in the associated *detloc* tuple.

In summary, the results of analyst review are written to the DBMS in a way that allows the analyst and *ASSESS* solutions to be compared in detail. This comparison is done by the *PerfV* process described in the following section.

† **Intelligent Array System User Documentation**, SAIC-89/1737, December, 1989.

‡ The *status* attribute in the *loc* relation.

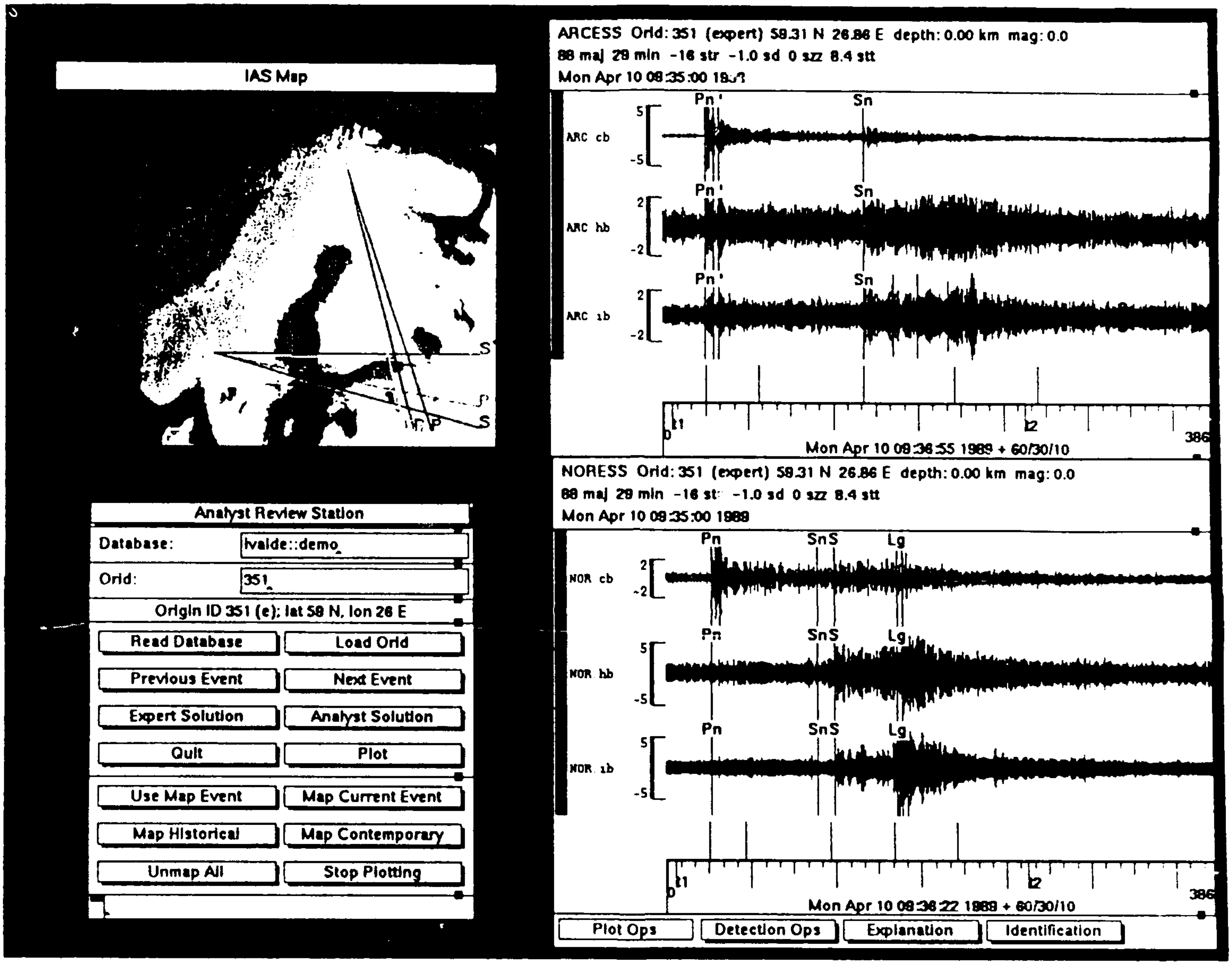


Figure 4.9. A typical "Analyst Review Station" display of an event solution (denoted by unique Orid) obtained by *ASSESS* (denoted "expert"). The functions of the buttons on the "Control Panel" at the lower left are described in the *IAS* user documentation. The waveform display shows three standard beams (see Section 3.8) from each array. All detections in the time segment displayed are indicated by their phase identifiers. Vertical lines below the phase identifier indicate that the phase is associated with the current Orid (i.e., Orid 351). The expected arrival times for Pn, Pg, Sn, Lg (and Rg at ARCESS) are computed for the location solution and shown as vertical lines just above the time axis. The event solution has been sent to the map program, and each phase is plotted with a line at the estimated azimuth. The location and confidence ellipse for the solution are also plotted.

4.7. KNOWLEDGE ACQUISITION

The concept for knowledge acquisition in *IAS* was described in Section 2.4. In the current implementation this concept is implemented in the *PerfV* (performance validation) software module. The primary function of this module is to compare the analyst and *ASSESS* solutions to determine which elements of the knowledge base have implicitly been "validated" and "invalidated" when the analyst approves and corrects the *ASSESS* solution. This module also constructs a "summary relation" which summarizes the most important information about each event solution in an easily manipulated form. Another important aspect of the knowledge acquisition concept is a user-friendly interface to make it convenient for seismologists to retrieve and organize information to guide the development of new knowledge to be input to the system. In this section each of these aspects of the *IAS* knowledge acquisition modules are described in more detail.

4.7.1. Performance Validation

In the previous section the DBMS links between *ASSESS* and analyst solutions were described. The important relations for maintaining the two solutions and the links between them are *detection, detloc, loc, locnorid* and *locporid.* The *PerfV* process scans these relations to find linked pairs of *loc* and *detloc* tuples.† Rule-based reasoning is used to decide which element of the *ASSESS* reasoning process made the decision that was overruled by the analyst change.

As described in Section 4.3.4.1, the *ASSESS* reasoning process is divided into seven sequential KS classes, and seven sequential tuples are written to the *audit* relation to identify the KS used to make the decision in each class. The *PerfV* rules select the KS class where the "error" was made. The audit record for this KS class is marked "invalid," and the audit record for earlier (in the sequence) KS classes is marked "valid." Audit records for KS classes later in the sequence are then marked "ignored" since the error may have contaminated later steps in the reasoning process. In some cases the error cannot be unambiguously attributed to one KS class, and two classes are marked "invalid." If there are KS classes between the two in the sequence, they are marked "ignored." For valid events *PerfV* marks the audit records "valid" for all KS classes.

The rules in the current implementation of *PerfV* are listed in this section according to the KS class or classes inferred to be the cause of the *ASSESS* error. The first group of rules examines the changes made to individual phase arrivals, and the second group looks at sets of phase arrivals. Each phase arrival has a *detection* tuple identified with an arid, and each event solution has a *loc* tuple identified with an orid. The rules for individual phase arrivals are:

<u>Signal Processing KS Class</u>

- If two linked *detloc* tuples are associated with *detection* tuples that have different arid's, the analyst has retimed the phase.
- If the second of two linked *detloc* tuples has *detloc.phase* = "glitch," the analyst has discarded this *SigPro* detection as a false alarm.
- If the second of two linked (via the *locnorid* relation) *loc* tuples is associated with a *detloc* tuple with *detloc.pdlid* = "null," the corresponding *detection* tuple has been added by the analyst.

† *PerfV* can be initiated each time the analyst completes an event, but it is more convenient to run it in a batch mode (e.g., once a day). As was done several times during the initial period of *IAS* operation in late-1989, *PerfV* can be changed and rerun over the entire database (though this requires approximately one hour of computer time per 100 events).

Initial Phase Identification KS Class

- If two linked *detloc* tuples have the same arid and *detloc.phase* differs in phase "type," the analyst has overridden the initial phase identification made by *ASSESS*. The phase types are P (P, Pn, Pg), S (S, Sn, Lg, Rg), N (noise) and T (teleseism).

Detection Grouping KS Class

- If two linked *detloc* tuples are associated with *loc* tuples not linked via the *locnorid* relation, and are not from the same detection group, the analyst has disassociated this phase from one event and associated it with another event.

Phase Association KS Class

- If two linked *detloc* tuples are associated with *loc* tuples not linked via the *locnorid* relation, and are from the same detection group, the analyst has disassociated this phase from one event and associated it with another event.

Final Phase Identification KS Class

- If two linked *detloc* tuples have the same arid and *detloc.phase* differ within the same phase "type," the analyst has changed the identification of this phase.

For the following rules we compare patterns in the "initial detection group" (Section 4.3.2.2) generated by *ASSESS*, the "*ASSESS* detection set" associated with each orid created by *ASSESS*, and the "analyst detection set" associated with each orid written by the analyst. The rules are:

Detection Grouping and Phase Association KS Classes

- If there is a detection in an *ASSESS* detection set which is not in any analyst detection set, the analyst has removed this detection from the *ASSESS* solution and not associated it with another event.
- If there is a detection in an analyst detection set which is not in any *ASSESS* detection set, the analyst has associated this previously unassociated detection with an event.
- If there is one *ASSESS* detection set that is a subset of an initial detection group, and there are two or more analyst detection sets which include detections in this initial detection group, the analyst has invalidated the *ASSESS* decision that there is only one event with detections in this initial detection group.

Phase Association KS Class

- If there are two *ASSESS* detection sets which are subsets of an initial detection group, and there are m analyst detection sets ($m \neq 2$) which include detections in this initial detection group, the analyst has invalidated the *ASSESS* decision that there are two events with detections in this initial detection group.
- If there is one *ASSESS* detection set that is a subset of an initial detection group, and there are two analyst detection sets which are both subsets of the same initial detection set, the analyst has created two events where *ASSESS* found only one.

Event Grouping and Network Location KS Classes

- If >1 stations contribute to the *ASSESS* solution and the analyst associates with this event one or more detections previously associated with one or more single-station solutions, the analyst has invalidated the decision that these detections belong to different events.
- If >1 stations contribute to the *ASSESS* solution and the analyst associates with this event one or more previously unassociated phases, the analyst has invalidated the decision that these detections are not with any event.

- If 1 station contributes to the *ASSESS* solution, and the analyst associates with this event one or more detections from a different station, the analyst has invalidated the decisions that this is a single-array event and the detections belong to other events or no event.
- If > 1 stations contribute to an *ASSESS* solutions which contains exactly two phases, and the analyst invalidates this solution, the analyst has invalidated the decision that these detections belong to the same event.
- If > 1 stations contribute to an analyst solution which contains exactly two phases, and the detections were not previously associated with an *ASSESS* solution, the analyst has invalidated the decision that these two detections are unassociated. solution, the analyst has invalidated the decision that these detections belong to the same event.

Phase Association, Event Grouping and Network Location KS Classes

- If two linked *detloc* tuples have the same arid, and *detloc.phase* differs within the same phase "type," and either an Sn was changed to an Lg, an Lg to an Sn, a Pn to a Pg, or a Pg to a Pn, the analyst has changed the identification of a defining phase.

4.7.2. Summary Relations

Summary relations are computed to characterize the gross features of event solutions and any differences between the automatic (*ASSESS* and analyst results. They are generated by a portion of the *PerfV* software module which extracts the relevant information about events from the database, computes summary information, and inserts this information in the summary relations. In this section we describe in detail the summary data computed during the Fall, 1989, operation of *IAS*. We note that these relations are easily changed and expanded. That is, if new summary data are needed, the *PerfV* module is modified appropriately. It can be applied to the entire database of past events if desired.

There are two summary relations in the current implementation of *IAS*, as described below. This is followed by a list of the attributes found in each of these relations.

1. *ev_summary*
   This provides a concise summary of important characteristics of each event solution. There is an entry in the relation for each final location produced by *IAS* (i.e., validated *ASSESS* location or analyst location).
2. *ex_an*
   This relation has an entry for each linked pair of *ASSESS* and analyst solutions that summarizes the major differences between the two. It also has an entry for events added by the analyst, though most attributes are "null."

The entries in each of these relations are described below.

ev summary

orid Unique identifier for an origin (location solution).

nearsta The nearest station to the location.

neardist The distance to *nearsta*.

nearaz The azimuth from *nearsta*

refid The identifier of the nearest "reference point." The *IAS* managers can specify these locations of special interest (e.g., mines) as they think appropriate. The database includes a relation (*ref_loc*) describing them.

refdist	The distance to the nearest "reference point."
refaz	The azimuth to the nearest "reference point."
grn	The Flinn-Engdahl geographic region number.
nsta	The number of stations with defining phases associated with the event.
lsta	The number of stations with associated phases that are within 250 km of the event.
asta	The number of arrays with associated phases that are at a range between 250 and 2000 km.
rsta	The number of non-array stations with associated phases that are at a range between 250 and 2000 km.
tsta	The number of stations with associated phases that are at teleseismic distances (> 2000 km).
ndef	The number of defining phases (i.e., Pn, Pg, Sn, Lg, Rg) associated with the event.
adef	The number of associated, nondefining phases (i.e., P and S)
primp	The number of primary phases (first P, usually Pn) associated with the event. Note that this is mainly for teleseismic data, and *primp* = *nsta* in *IAS*, except when the associated phases at a station do not include Pn or Pg.
secondp	The number of secondary phases (i.e., associated defining phases after first P) associated with the event.
depthp	The number of depth phases (e.g., pP, sP) associated with the event.
lddate	The date these summary data were inserted into the database.

ex_an

forid	A unique identifier for a location produced by the analyst
eorid	A unique identifier for a location produced by the expert system.
ddist	The distance between the *forid* location and the corresponding location for *eorid.*
ddepth	The depth difference between the *forid* location and the corresponding location for *eorid.*
dtime	The origin time difference between the *forid* location and the corresponding location for *eorid.*
did	The event identification difference between the *forid* location and the corresponding location for *eorid.*
dnsta	The difference in the number of recording stations (*eorid* - *forid*) for the two locations.
dlsta	The difference in the number of local stations (range < 250 km) associated with the event.
dasta	The difference in the number of regional stations (range between 250 and 2000 km) associated with the event.
drsta	The difference in the number of non-array stations associated with the event.
dtsta	The difference in the number of teleseismic stations (range > 2000 km) associated with the event.
dndef	The difference in the number of defining phases associated with the event.

dprimp The difference in the *primp* for the event.

dsecondp The difference in the *secondp* for the event.

ddepthp The difference in the number of depth phases (e.g., pP, sP) for the event.

rprimp The number of P-type phases in the analyst solution (*forid*) for which the phase identification was changed.

rsecondp The number of S-type phases in the analyst solution (*forid*) for which the phase identification was changed.

rdepthp The number of depth phases in the analyst solution (*forid*) for which the phase identification was changed.

added The number of phases added to the event solution by the analyst.

retime The number of phases that are in both the analyst and expert system solutions, but have been retimed by the analyst.

splitev Indicates when the analyst solution includes detections which were associated with two or more solutions by the expert system.

multev Indicates when there is another event solution within 50 km which has an origin time that differs by less than 5 minutes.

lddate The date these summary data were inserted into the database.

4.7.3. User-Interface

The *IAS* database provides a rich source of information about seismic events and comparisons between automatically generated and human-generated solutions. Tools to retrieve this information fall into three classes:

1. SQL Queries
   The most flexible and complete method for retrieving data from the DBMS is directly via the DBMS query language, SQL. This requires knowledge of SQL, but this is not very difficult to acquire. A more significant barrier to effective use of SQL is the requirement for an intimate knowledge of the *IAS* database itself. This is not simply knowledge about the relations and their interconnections (which is straightforward to learn from the documentation), but also includes knowledge about the number of tuples in specific relations and its effect on performance which comes mainly with experience. Nevertheless, users requiring intense interaction with the DBMS over an extended period will probably use SQL queries extensively.
2. Standard Output and Menu-Based Retrieval
   The standard output of *IAS* includes a bulletin (produced by the *bull* process, hardcopy display of the solutions (produced by *EvPlot*), and dynamic display of solutions, explanation, etc., via *ARS* (Section 4.6). The bulletins are published and distributed by the Center for Seismic Studies,† and they include numerous *EvPlot* displays (see Section VI for examples). Also falling within this category are the *DBS* process and the "Executive Review Station" (*ERS*), and these are described in later subsections.
3. Natural-Language Interface
   The SQL queries have unlimited flexibility, but require great knowledge of the system to

† As of February, 1990, bulletins have been published for 1 October to 18 November, 1989. Request copies of these and subsequent bulletins (starting in January, 1990) from Center for Seismic Studies, Suite 1450, 1300 N. 17th Street, Arlingon VA 22209-3871.

use effectively. The standard output and menu-based retrieval systems are very easy to use, but have limited flexibility. What occasional users most need is an interface that is both flexible and easy to use. An interface that provides an important advance toward this objective is the *iastalk* process described in a later subsection.

4.7.3.1. *The Database Browser/Sector (DBS) Process*

The *DBS* user-interface is the form shown in Figure 4.10. The user fills in this form (or uses the default values) to bound a query to the *loc* relation. The results of this query are listed by *loc.orid* in a "results" window. Orid's of interest can then be selected and sent via IPC messages to other *IAS* processes;† currently, these are *map, ARS, DA, Review, Run, MERSY, EvPlot*. Further details on this process are provided in the *IAS* **User Documentation**.

4.7.3.2. *The Executive Review Station (ERS)*

This process provides a high-level interface to the *IAS* database (see the *IAS* **User Documentation** for a detailed description). The user-interface is a slightly modified *DBS* form and maps provided by the *map* process. Selected events are plotted on the selected map. The *IAS map* process allows selection of maps at many scales and several projections. The largest map is a Mercator projection of the earth's surface between ± 75° latitude. Also, there are azimuthal-equidistant projection maps of the area within 2000 km of the NORESS array at two scales. Measured horizontally on a 16-inch screen, the scale of these maps is approximately 170 km/cm and 43 km/cm. These large-area maps were made by processing elevation data from World Data Center A. For selected areas in the northwestern Soviet Union, there are also maps at a scale of 11 km/cm made by processing DMA digital terrain elevation data and selected feature data. SPOT images can also be displayed for a few selected areas at a scale of ~2 km/cm on a 16-inch monitor.

Events can be selected by a point-and-click interface to the map. Information about the selected event (location, magnitude, event identification, etc.) can be obtained in this way. Thus, the *ERS* provides a good interface for browsing location information in the database. Waveforms cannot be examined with this interface.

4.7.3.3. *The Natural-Language Interface*

The ability to retrieve data from a relational database by typing English queries has obvious advantages. Many products to provide this capability are under development in both large companies and small startup companies funded by venture capital. The technology is still in its infancy, and there are major problems that remain to be overcome before it can realize its promise.

The *iastalk* process is implemented with the "NL" product developed by Natural Language, Inc. This product was selected after evaluation of several alternatives. Basically, it works by parsing English questions to generate SQL queries to the DBMS. Natural-language parsing is a major topic of current research in computer sciences, and the designers of NL (Jerrold Ginsparg and John Manferdelli) are among the leading participants.

Natural Language (NL) customization requires a thorough understanding of the problem domain. It involves a mapping of the English constructs used by seismologists to the corresponding relational database entities (relations and attributes). For *IAS* this mapping was done for the *loc, detloc, detection, locnorid, locporid, ev_summary, ev_an* and *audit* relations. This means that attributes stored in these relations can be obtained with English queries that

† See Section III for a description of these processes and IPC messages.

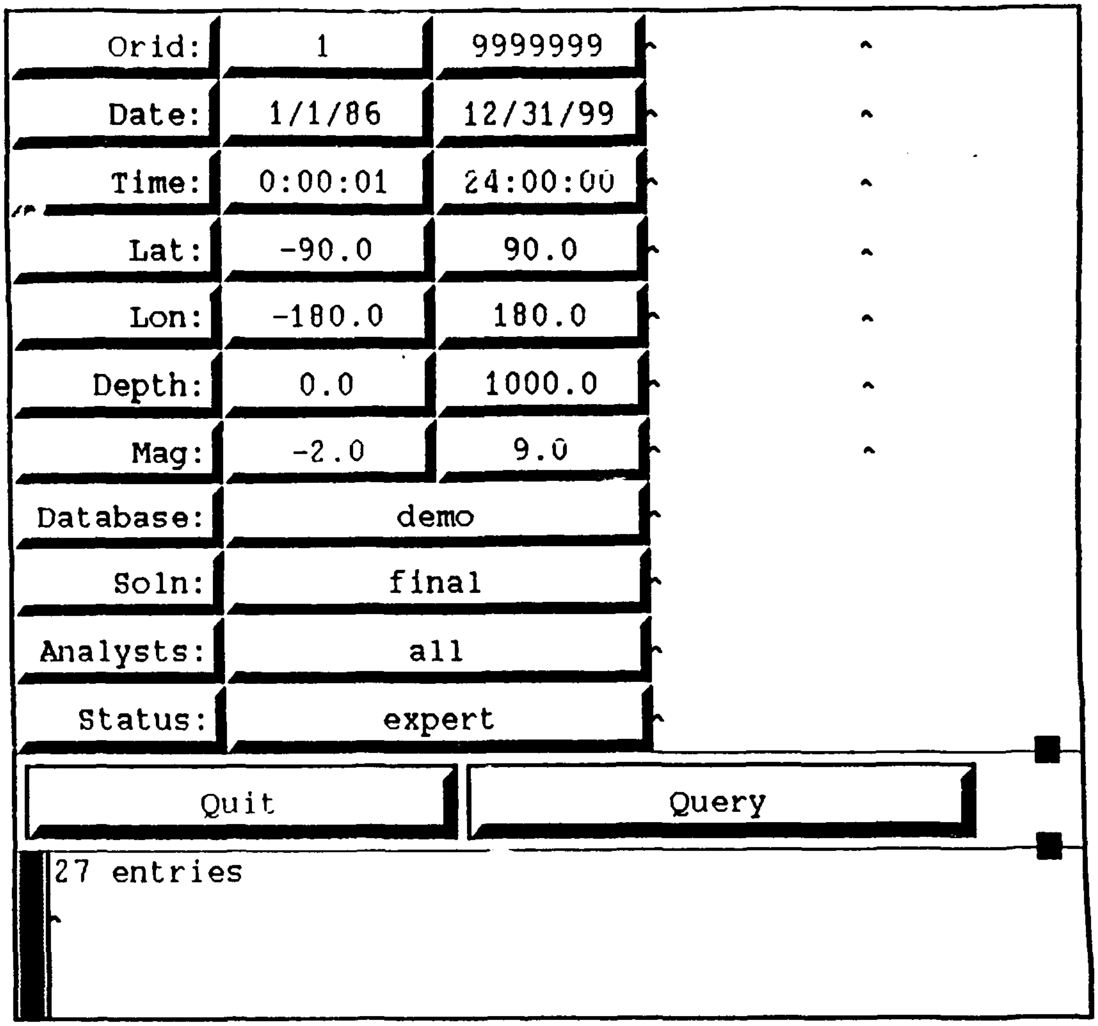


Figure 4.10. The DBS user interface is shown with default values for the upper and lower bounds on each attribute in the form. The user can change any of these bounds by typing in the appropriate space at the right. The number of table entries satisfying the specified bounds is returned in the window at the bottom when "Query" is selected. In this case *Database:demo* has only 27 entries.

the NL parser is able to understand and construct the appropriate SQL. The parser must apply much knowledge and reasoning ability to resolve (or recognize and request clarification) ambiguities in typical queries made by seismologists. Since the knowledge-base included with the NL product is oriented toward business applications, the seismology-specific meaning of terms like distance, time, location, etc. had to be added.

The NL product was customized by SAIC and NLI (under subcontract) using a list of about 150 typical queries. These queries and straightforward variations of them are understood by the current version of *iastalk*. However, there are deficiencies of this version that limit its utility for general use as an interface to the *IAS* database. One deficiency is that it has been customized for only a portion of the database (albeit the most interesting relations for most purposes). Also, there are knowledge-base gaps, so *iastalk* may fail to understand different formulations of queries it does understand. More serious deficiencies arise as a side-effect of the flexibility that is one of the most attractive aspects of the natural-language interface. These are:

- Experience shows that seismologists are remarkably imprecise in their queries. Thus, they must learn by experience to state clearly what they want. This is a frustrating process for the novice user, since the training takes place by through trial-and-error.
- The flexibility allows the user to make impractical queries requiring a linear-search of large tables.

Thus, *iastalk* provides an interesting, but not yet practical interface to the *IAS* database for novice users. Work is continuing under another project (NMRD) to provide a more structured interface ("NL Query") to NL to overcome the limitations outlined above. This interface will provide guidance to make practical queries that are guaranteed to parse. This introduces some limitations on the flexibility, but the NL Query interface will be more flexible than *ARS*, *DBS*, etc., and far easier to use than direct SQL queries.

V HARDWARE ARCHITECTURE

The computer configuration used for operation of *IAS* October-November, 1989 is shown in Figure 5.1. The LAN's at the Center and at NDAC are shown in separate drawings. The two are connected with a Proteon gateway implemented on Proteon 4200-10 computers at the two sites. The Proteon units route inter-LAN packets over the satellite link, creating a wide-area network (WAN).

As shown in Figure 5.1, *IAS* is implemented on seven Sun workstations plus an IVAS image processing and display system (Section 4.6.x). Each Sun workstation is identified by model number and monitor (C is 19" color, M is 19" monochrome, HM is 19" high-resolution monochrome, CE is 16" color, S indicates no monitor). The computers are named for figures in Norwegian mythology,† and these names are indicated. Also shown for each computer is the number of megabytes (MB) of physical memory and any attached disks (indicated by unformatted capacity). The IVAS is an image display device, and it includes an interface board installed in Mimer (indicated by a line in Figure 5.1b) to use the Sun CPU for image processing.

There are many acceptable ways to install the software on this hardware configuration. In the figure we show the installation used for most of the October-November, 1989 operation of *IAS*. Only the major processes among the 43 listed in Section III are shown. The others (for example, the various "agents") are small enough to be installed almost anywhere.

The freedom to move processes from one machine to another is limited by requirements for effective performance. Some of the performance requirements are objective (maintain pace with the real-time data stream) while others are more subjective ("adequate" response to user requests). A Sun 4/260 can handle the *SigPro* processing for a single array, even if an Ingres or Oracle DBMS is sharing the machine (Figure 5.1a). However, a less-capable machine (e.g., Sun 3/260) would not be adequate for this processing. At the Center (Figure 5.1b) *ASSESS* and the DBMS each require a Sun 4/260 with large physical memory (32 MB) for satisfactory performance, so they cannot coexist on the same machine. Lisp processes (see below) usually require 16 MB memory for satisfactory performance, though the *Manager* performance is satisfactory with less.

Since the X Window System is used for all graphics, the screen displaying the output of a process (the X Window "server") can be anywhere on a LAN shared with the computer executing that process (the X Window "client"). The main user-interface processes are *ARS* and *Map*, and these processes are most effective when the X Window server is on a Sun 4 (4/110, SparcStation, or larger) with at least 16 MB memory. The map program requires a color monitor. The other graphics produced by the system can be displayed on either color or monochrome.

The *IAS* system requires the following licenses for commercial software products:

<u>Relational DBMS</u>

Ingres An 8-user Ingres license is required for operation at the Center. During the first part of the October-November operation, Ingres was used at NDAC. A change was made to Oracle, which has been used for the *SigPro et al.* DBMS since.

Oracle A 16-user (the smallest increment) Oracle license is required for the signal processing part of the *IAS* at NDAC.

† For example, see E. B. Tichenell, *The Masks of Odin*, Theosophical University Press, 1985.

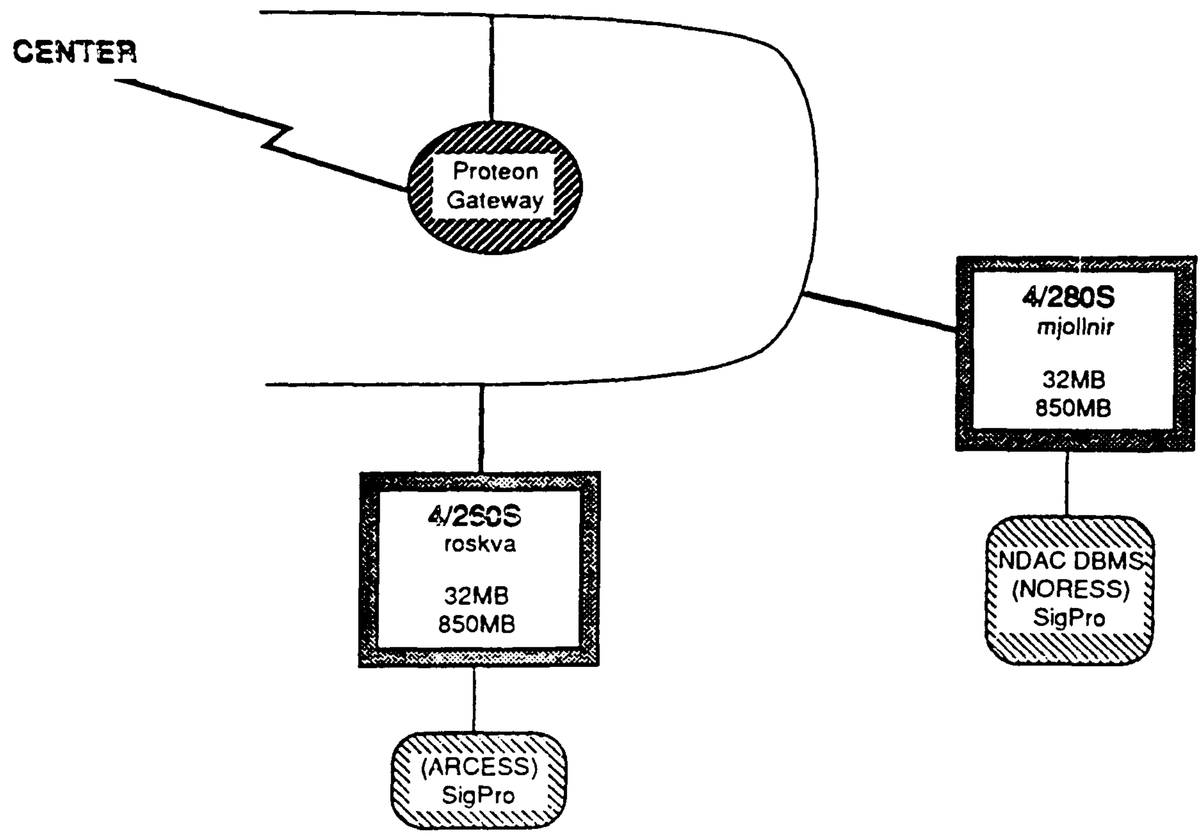


Figure 5.1a. The NDAC LAN with the installation of major software processes during October - November, 1989.

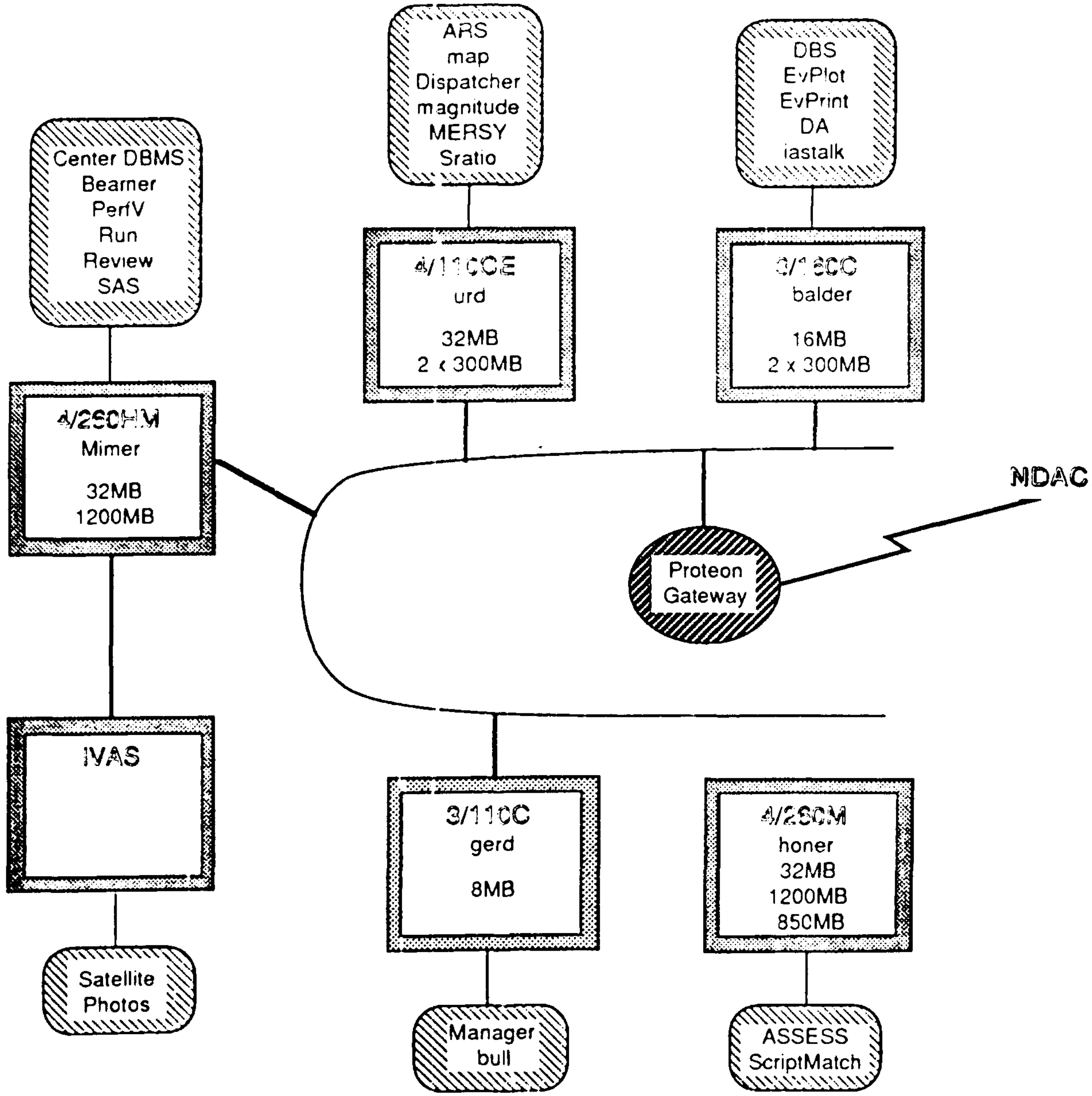


Figure 5.1b. The Center LAN with the installation of major software processes during October - November, 1989.

LISP

Franz Allegro CommonLisp is required for *ASSESS*, *PerfV*, *Manager* and *ScriptMatch*.

Natural-Language Interface

NLI The Natural Language licensed by Natural Language, Inc. is required for *iastalk*.

NCAR Graphics

Minesoft A commercial version of NCAR graphics software licensed by Minesoft, Inc. is required for the hardcopy plots produced by *EvPlot*.

X Window System

MIT This portable standard for network graphics is available at no cost from MIT's Project Athena.

PostScript Translator

Adobe This product is required to convert text (from troff) and graphics (e.g., from Minesoft graphics) to a form compatible with PostScript laser printers.

VI PROCESSING EXAMPLES

6.1. Format

The examples are summarized in Table 6.1. Each is identified by a sequence number which identifies the figures detailing this example. Also listed in the table are the approximate origin time (*mmddhhmm*) computed by *ASSESS* and the difference between the *ASSESS* and analyst solutions. This difference is characterized by two attributes from the *ex_an* relation (Section 4.7.2). The *dndef* is the difference in the number of defining phases, and the *ddist* is the distance separating the *ASSESS* and analyst locations. The "Dist. to Hel." is the separation between the *IAS* analyst location an independent network location. Many of these events were not detected by this large network.

The figures are produced by the *EvPlot* process. The *ASSESS* and analyst solutions appear on facing pages in the same format. Each includes a listing of the results, waveforms from both arrays, and a map. At the top is the final solution, with SMaj, SMin, Strike characterizing the 90% confidence limits on the location solution. The single-array locations are also listed, and comparison with the multiple array locations shows the advantage of the second array. All detections in the waveform time window are listed with their phase identifier and various quantities determined by *SigPro* (Section 4.1). These are the origin time, the standard deviation on the origin time (Tsd), the beam identifier (Bmn, see Table 4.1), four quantities from the f-k solution (Vel, Dvel, Azim, Asd), the short-term average amplitude (Stavg) on the detecting beam, the frequency determined during the analysis of the detecting beam, and the f-k quality (Fkq). The P and Spl are the *Ppolar* and *Spolar* described in Section 4.3.2.3. The Orid is a unique event identifier. Phases with the same Orid are associated with the same event. In the detection listing for the analyst solution there are usually entries with "??" in the column for the phase identifier. This shows the original *SigPro* attributes for a detection that has been retimed by the analyst. The amount of the change can be seen by comparing the "??" entry to the entry that is identical except for the origin time and Orid. Also, when the analyst adds a phase, the *SigPro* quantities are not computed, so analyst added detections have "-1" in the attribute columns. Events located by the Helsinki bulletin show that location on the analyst solution. Precision of 3 digits indicates that the Helsinki analyst located the event in a known mine based on the waveform patterns.

The waveform displays show 7 minutes of three standard beams from each array. The beam marked "CB" is a coherent beam of all vertical channels filtered at 4-8 Hz, and steered toward the estimated location at an apparent velocity of 8.1 km/sec. The "HB" is an infinite velocity incoherent beam of the horizontal channels filtered at 1-4 Hz. The "IB" is an infinite velocity incoherent beam of all vertical channels filtered at 1-4 Hz. All detections in the time window are marked with their phase identifier. A vertical line through the seismograms marks detections associated with the event plotted on the map. The theoretical arrival time of the four main regional phases expected from that location are marked at the bottom of each display, and the time window for the plot begins 30 seconds before the theoretical Pn arrival time. The map shows the location, confidence ellipse, and azimuth of the defining phases. Phases added by the analyst have no azimuth, so these new phases do not appear on the map.

In the following pages each of the examples in Table 6.1 is detailed with figures showing the *ASSESS* and analyst solutions along with comments on the most important features of each example. The comments are given in subsections organized according to the subheadings in the Table.

TABLE 6.1
Comparison Between *ASSESS* and Analyst Solutions

#	Origin Time	*dndef*	*ddist* (km)	Dist. to Hel.(km)†	Comments
			Correct Solutions by *ASSESS*		
1	11161221	0	0	-	Validated
2	10290212	0	32	-	Minor retiming
3	11011559	0	3.5	10	Minor retiming
			Refinement by Adding Detections		
4	10311955	2	37	21	Questionable phases added
5	11011814	2	18	-	Emergent Lg undetected
6	11021214	3	19	25	Questionable phases added
7	11101042	2	89	-	Interfering phase
8	11161224	2	22	45	Questionable Sn added
			ASSESS Confused by Missing Detections		
9	11011225	2	194	31	Missing Sn at NORESS
10	11011302	2	250	23	Missing Sn at ARCESS
			Single Array Solutions		
11	11011239	0	58	-	Error due to precurser
12	11010816	2	22	-	1 event or 2?
13	11011144	1	161	-	Incorrect Pg
14	11011237	1	174	-	2 events
15	11012332	1	61	-	3 events
			Rejected Events		
16	11010740	2	-	-	Invalidated Lg + Lg
17	10311244	2	-	-	Invalidated Sn + Lg
			Difficult Cases		
18	11011228	0	649	55	Ambiguous solution
19	11020942	0	308	-	False corroboration
			Mixed Events		
20	11020819	3	22	-	Multiple explosion in mine
21	11020820	0	403	-	Multiple explosion in mine
22	11040700	-	-	-	Rejected solution
23	11040701	1	278	25	Multiple explosion in Baltic Sea
24	11040703	1	261	25	Multiple explosion in Baltic Sea

†Distance between the *IAS* analyst location and the location in the University of Helsinki bulletin (recent editions list 98 contributing stations in the Nordic countries.) The "-" indicates that the event does not appear in that bulletin.

6.2. Correct Solutions by *ASSESS*

A few examples illustrate that *IAS* often obtains excellent solutions:

1. <u>A valid single-array solution</u>
   The system has no difficulty with simple local events such as the ARCESS solution shown which was "validated" by the analyst (no changes). By coincidence, a local event occured north of NORESS in this time window, and the analyst changed the *ASSESS* solution only slightly to add Pg.

2. <u>Minor retiming of a multiple-array solution</u>
   The onset time estimator in *SigPro* does not do very well in picking the onset time an analyst prefers. Thus, the analyst often makes adjustments to the onset time, and these almost always tighten the confidence bounds on the solution. In this example the analyst has retimed the two Pn phases, moving the location 32 km, and reducing the confidence bounds significantly. A Pn from another event and two apparent teleseisms also appear in the ARCESS window.

3. <u>Minor retiming of a multiple-array solution</u>
   Again, the analyst has retimed both Pn phases, but this time by so little that the location moved by only 3.5 km. The Helsinki bulletin put this event in a mine, and both solutions are within 10 km of its location which is only given to the nearest 0.1° (about 5.5 km in latitude).

6.3. Refinement by Adding Detections

The analyst often sees detections that *SigPro* missed, but is sometimes guided by the theoretical arrival times to pick detections that would not otherwise be picked. It is debatable whether operational policies should allow these otherwise undetectable phases to be added by the analyst, but it was allowed under policies in force at the time these data were reviewed.

4. <u>Adding subtle detections</u>
   In this example the analyst has added very subtle detections at NORESS. Without the guidance of the theoretical arrival times it is unlikely that these would be picked. This example also illustrates another subtle change at ARCESS. The analyst has shifted the Lg from the last to the second of the four detections in the Lg wavetrain. These changes and the retiming of both Pn move the location by 37 km, though well within the confidence limits on the *ASSESS* solution. As can be seen in the detection listings, *ASSESS* formed and the analyst rejected a two-phase, two-array event with the late Lg at NORESS and Sn at ARCESS. This is common, and will be discussed in Section 6.6.

5. <u>Adding Detections</u>
   The emergent Lg at NORESS is easily seen (though difficult to time), and was added by the analyst. These are very difficult phases for the automatic detector. The Sn was detected at ARCESS, but *ASSESS* failed to identify it. The analyst added this Sn. These changes together with retiming several phases move the location 18 km.

6. <u>Adding Detections</u>
   The analyst added a rather subtle Sn at NORESS and very subtle Sn and Lg at ARCESS. The result is a shift of the location by 19 km. The complex pattern of detections at the end of the segments can be partially understood by studying the listings. There is a local event at NORESS, and Pn at both arrays from a larger event.

7. <u>Adding Detections</u>
   Here the analyst validated *ASSESS* for NORESS except for some minor retiming, but added subtle Sn and Lg at ARCESS. This Sn is obscured by a regional P (velocity 6.1 km/sec) arriving from the northwest. These changes move the location by 89 km.

8. <u>Adding Detections</u>
In this example the analyst added a questionable Sn at ARCESS and changed the undefining P at NORESS to Pg. The location moved 22 km as a result.

6.4. *ASSESS* Confused by Missing Detections

These two examples of events occuring 37 minutes apart show the difficulty of developing rules that work in general even for fairly small regions. In these examples the problem is with the rules for deciding whether an S detection is Sn or Lg. Experience with examples like these has led to new rules which will be implemented in the next version.

9. <u>Missing Sn at NORESS</u>
The subtle Sn at NORESS was not detected, but one of the detections of Lg was on a horizontal beam (Bmn = 221), so *ASSESS* identified it as Sn. The Sn was also missed at ARCESS, but the Lg was identified correctly. Fixing the error and adding the missing phases moves the location by 194 km, which is about 30 km outside the confidence ellipse on the first solution.

10. <u>Missing Sn at ARCESS</u>
The NORESS detections are similar to those in the previous example, but this time the Sn was detected instead of Lg, and the rules identify it correctly. However, the same rules fail at ARCESS where Lg was detected instead of Sn (the main problem is that too much weight is given to the fact that Sn is detected on horizontal beams more often than Lg). The analyst also added Lg at NORESS, though the timing would be questionable without the guidance of the expected arrival time. Making these changes, the analyst moves the location by 250 km.

6.5. Single Array Solutions

Small events are detected on only one array. Example #1 showed an easy local event. In this section we give other examples illustrating problems that occur. The rules in the current generation of *ASSESS* are based primarily on NORESS experience. ARCESS is somewhat different, and rules specifically for this array are being developed by analyzing results of examples like those shown.

11. <u>NORESS Error Due to Precurser</u>
In this example a precurser P detection is incorrectly identified as the Pn for this local event. Both the low frequency and relative amplitude (with respect to Lg) make it obvious that this is incorrect, and the later high frequency, large amplitude P is actually the Pn. Correcting the error moves the location 58 km. Rules to account for relative amplitude and frequency content must be added to deal with situations like this.

12. <u>Ambiguous ARCESS Solution</u>
ASSESS identified Pn and Sn from the five detected phase. The analyst refined the solution by adding Pg and Lg (the times fit well) and doing some minor retiming. These changes move the location by 22 km, well within the confidence ellipse on either solution. Signals from explosions in mines on the Kola Peninsula are very common at ARCESS, but this location does not seem to be in a known mine. Also, the signals look different from typical mine blasts in this area. This suggests that these are actually signals from two explosions in the same mine about 7 seconds apart (the separation of the P detections). Either interpretation might be correct, and resolving the ambiguity requires examination of typical waveforms from many other events in the area.

13. <u>Incorrect Pg at ARCESS</u>
The P detected at ARCESS is incorrectly identified as Pg based on its polarization. Also, *ASSESS* failed to identify the Lg. Fixing these errors moves the location by 161 km, but again well within the large confidence ellipse on the *ASSESS* single-array location.

14. <u>Multiple Event at ARCESS</u>
Events in close succession at the same location are very difficult to unravel with data from a single array. Looking at the *ASSESS* ARCESS waveforms, the detections are Pn or Pg (the two are essentially the same at this range near the crossover), a stray S, Pn from the second event mixed with Lg from the first event, then Lg from the second event. *ASSESS* correctly concluded that there were ≥ 2 events in the sequenc ut failed to put them together properly (it was probably confused by the stray S detection). The analyst identified the first P as Pn, added a Pg 2 seconds later, and correctly identified the Lg. It appears that the analyst did not complete the solution for the second event at the same location.

15. <u>Multiple Event at ARCESS</u>
This is another complicated event at ARCESS with no detections at NORESS to help. Clearly, *ASSESS* incorrectly concluded that there was only one event. Careful study of the data suggests that there are probably three events separated by about 10 seconds. The analyst seems to have correctly picked the first of the three, but did not complete the solution. There are several possible interpretations that might be correct. In this case it appears that the two events are separated by only about 9 seconds, so *ASSESS* failed to see that there are actually two events. The analyst located the first event in the sequence correctly, but appears to have not completed the solution for the second (which is perhaps twice as large).

6.6. Invalidated Events

Waveforms are retrieved routinely for analyst review only when *ASSESS* forms an event. Therefore, the rules are designed to seek an event to explain as much of the data as possible. This bias toward false events reduces the possibility of missing true events. It turns out that about 25% of the event solutions constructed by *ASSESS* consist of one phase at each array. Unless the analyst is able to find additional detections, these two-phase, two-array solutions are routinely invalidated. The *EvPlot* output for two examples are shown on facing pages.

16. <u>Two Lg Location</u>
Two reasonable Lg detections are combined for the solution in this example. It could be a real event, but two Lg is not enough to validate it.

17. <u>Location from Sn and Lg</u>
This solution is less plausible than the previous example.

6.7. Difficult Cases

These examples show difficult events with weak signals.

18. <u>Misidentified Lg at NORESS</u>
The *ASSESS* solution is suspect due to the lack of energy around the expected Lg arrival time at NORESS. The analyst changed the NORESS Sn to Lg, but the result is a location that seems too far from the NORESS azimuths. However, the apparent energy near the ARCESS Lg arrival time gives this solution some credibility. The Helsinki bulletin locates this event within 55 km of the analyst location.

19. Misidentified ARCESS Pg
In this example the ARCESS Pn is misidentified as Pg during backtracking to find corroborating phases at NORESS (i.e., the Pg + Sn at ARCESS is corroborated by an Sn at NORESS). When the analyst corrects this error (also adding an Lg that appears undetectable), it becomes clear that the NORESS detections cannot be from this event.

6.8. Signals From Mixed Events

As noted previously (examples #14 and #15), events in close succession are difficult to unravel. However, several large explosions in close succession at the same mine are often seen in this area. Some examples are shown here.

20. 1st of a Multiple Event Sequence in Kola Peninsula Mine
In this complex sequence there are two sets of *ASSESS* and analyst plots. *ASSESS* correctly concluded that there were two Kola Peninsula events. The first is large enough to be detected at NORESS. The analyst corrected this solution by adding the Sn which was not detected at NORESS, adding the identification of Pg and Sn at ARCESS, and doing some minor retiming. The location is thereby shifted by

21. 2nd of a Multiple Event Sequence in Kola Peninsula Mine
This event appears to be in the same mine about one minute later. *ASSESS* entirely failed because *SigPro* failed to detect the P waves which can be seen before the Sn in the *ASSESS* solution. The analyst added both Pn and Pg and moved Lg to an earlier time.

22. Fictitious Event
This is a fictitious event arising from errors in the multiple event sequence (examples #23 and #24) and the coincidental detection of an S phase which was mistaken for an Lg from this fictitious event.

23. 1st of a Multiple Event Sequence in the Baltic Sea
These two events occured about 36 seconds apart at about the same location. Only the Pn were detected at ARCESS, but both Pn and Lg were detected at NORESS. *ASSESS* correctly recognized that there were two events with mixed signals at NORESS, but put them together incorrectly. The mistake was not corrected during network processing. The analyst rearranged the NORESS detections and correctly associated the ARCESS Pn. The location was moved to the east 278 km.

24. 2nd of a Multiple Event Sequence in the Baltic Sea
The second event follows easily from the solution from the first. The location moves to the west about 261 km.

Figures illustrating the examples in Table 6.1 appear in the following pages.

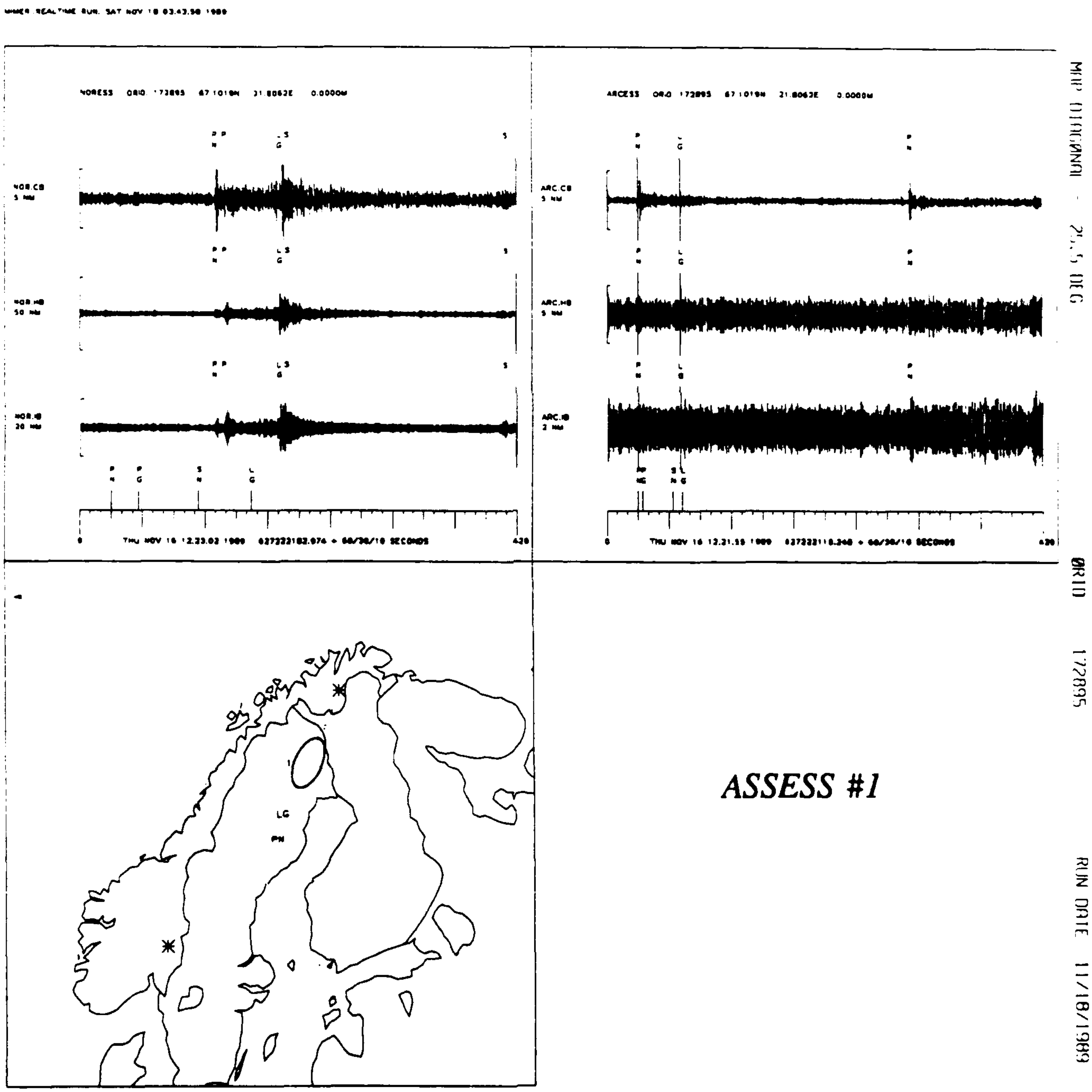
Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Thu Nov 16 12:21:39 1989	67.10	21.81	101.1	49.1	28.0

Thu Nov 16 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:25:11	1.6	277	9.5	2.7	124.1	6.5	356	3.75	1	-1/0	172891
P	12:25:21	3.0	266	9.2	2.5	107.5	6.2	203	3.75	1	-1/-3	172891
Lg	12:26:13	3.4	280	3.9	0.4	121.0	2.5	343	4.00	1	-1/0	172891
S	12:26:20	1.3	301	4.4	0.2	134.8	2.6	393	8.57	3	0/-1	172817
S	12:29:51	3.4	220	3.9	1.0	183.4	5.7	472	1.76	1	0/-3	172820

Thu Nov 16 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:22:25	2.8	286	8.0	1.3	209.7	5.6	108	5.45	2	0/-2	172895
Lg	12:23:06	3.7	225	3.9	0.3	211.9	3.0	161	5.00	2	0/-2	172895
Pn	12:26:46	1.9	279	7.8	1.7	193.1	4.9	123	4.00	1	0/-3	172891



ASSESS #1

PROCESSING EXAMPLES

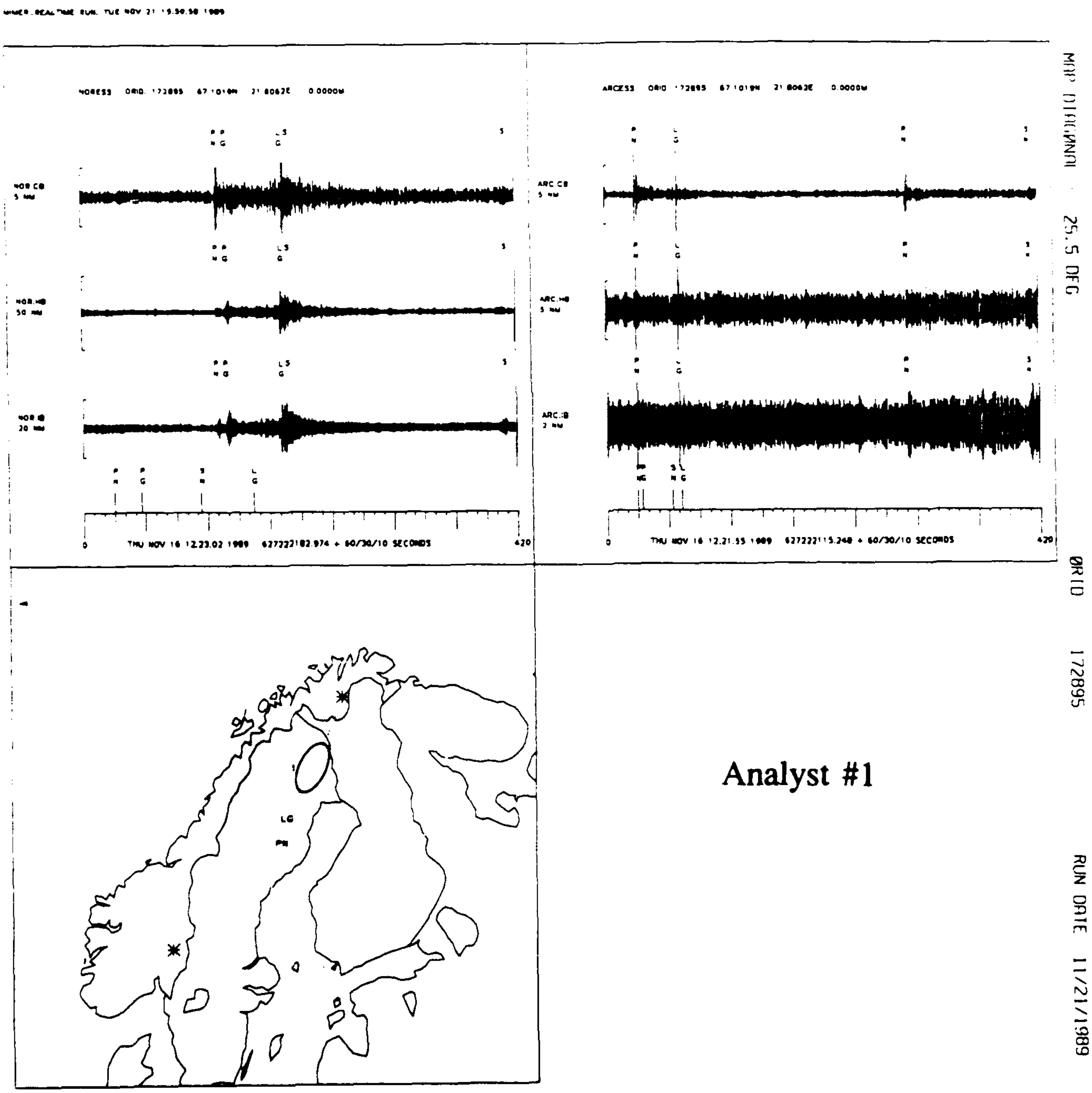
Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Thu Nov 16 12:21:39 1989	67.10	21.81	101.1	49.1	28.0

Thu Nov 16 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:25:11	1.6	277	9.5	2.7	124.1	6.5	356	3.75	1	-1/0	175004
Pg	12:25:21	3.0	266	9.2	2.5	107.5	6.2	203	3.75	1	-1/-3	175004
Lg	12:26:14	3.4	280	3.9	0.4	121.0	2.5	343	4.00	1	-1/0	175004
S	12:26:20	1.3	301	4.4	0.2	134.8	2.6	393	8.57	3	0/-1	172817
S	12:29:51	3.4	220	3.9	1.0	183.4	5.7	472	1.76	1	0/-3	172820

Thu Nov 16 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:22:25	2.8	286	8.0	1.3	209.7	5.6	108	5.45	2	0/-2	172895
Lg	12:23:06	3.7	225	3.9	0.3	211.9	3.0	161	5.00	2	0/-2	172895
Pn	12:26:46	1.9	279	7.8	1.7	193.1	4.9	123	4.00	1	0/-3	175004
Sn	12:28:45	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	175004



PROCESSING EXAMPLES

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Sun Oct 29 02:12:30 1989	54.96	16.13	114.0	77.9	59.5

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89/10/29 02:12.[illegible] 006	54 91	15 66	5 22	157 61	146 8	83.5	71.2
Assess(A)	69/12/31 23:59 59 000	-999 00	-999 00	16 99	26 17	-1.0	-1 0	-1.0

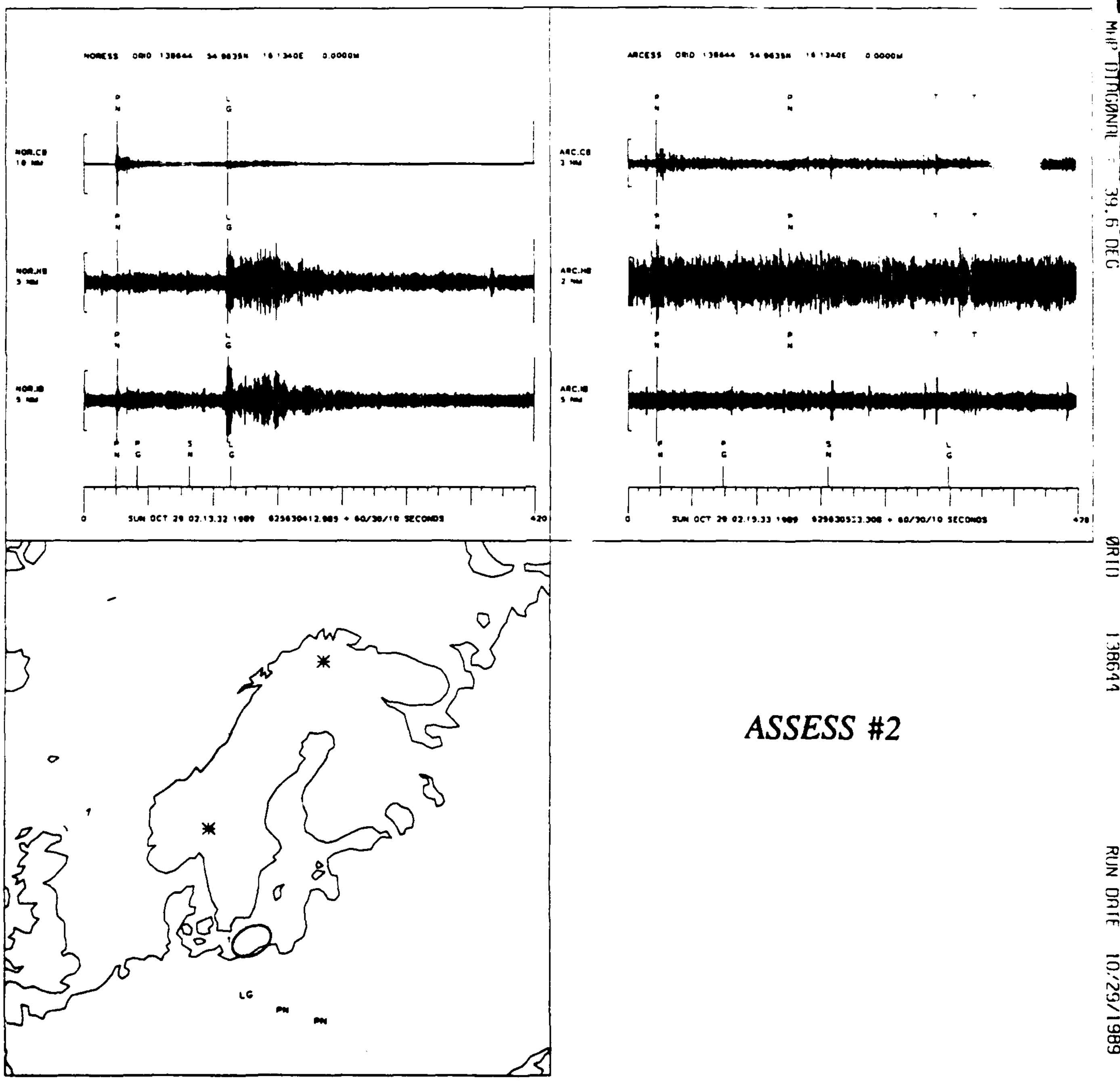
Sun Oct 29 1989 (N)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	02 14:03	1 0	285	9 0	1.8	153.3	4.6	288	5.00	1	0/-3	138544
Lg	02 15 46	3 5	264	5 0	1 0	162 6	4.8	87	2 61	1	0/-1	138544

Sun Oct 29 1989 (A)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	02.16:00	3 4	279	8.5	2.1	187.1	8 7	40	3 75	2	0/-1	138544
Pn	02.18:03	3 6	261	8.7	2 9	133 5	15 6	39	2 85	3	-1/0	138583
T	02:20:19	2 6	276	15 9	6 9	21 0	15 5	53	4 00	2	0/-3	138473
T	02:20:56	3.3	251	16 7	11 3	26 7	25 5	53	2 73	2	-1/0	138474

REALTIME RUN, SUN OCT 29 02:10:21 1989



ASSESS #2

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Sun Oct 29 02:12:28 1989	54.99	16.63	84.0	52.9	23.5

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N):	89/10/29 02:12:31.006	54.91	15.66	6.22	157.61	146.8	83.6	71.2

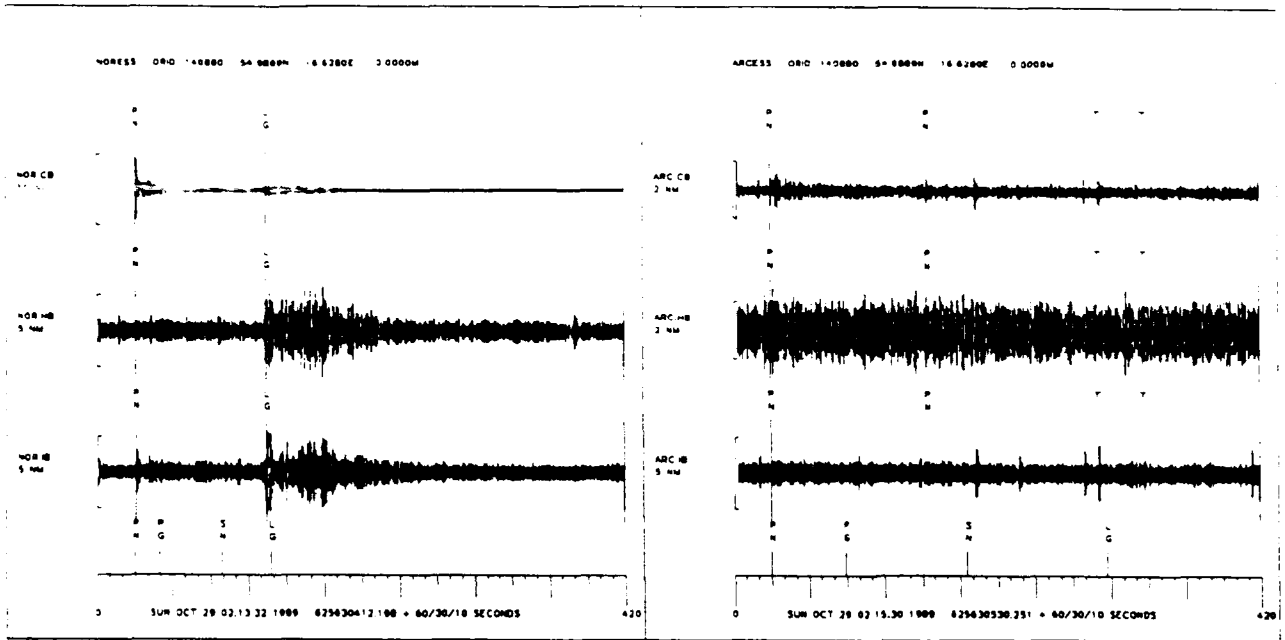
Sun Oct 29 1989 (N)

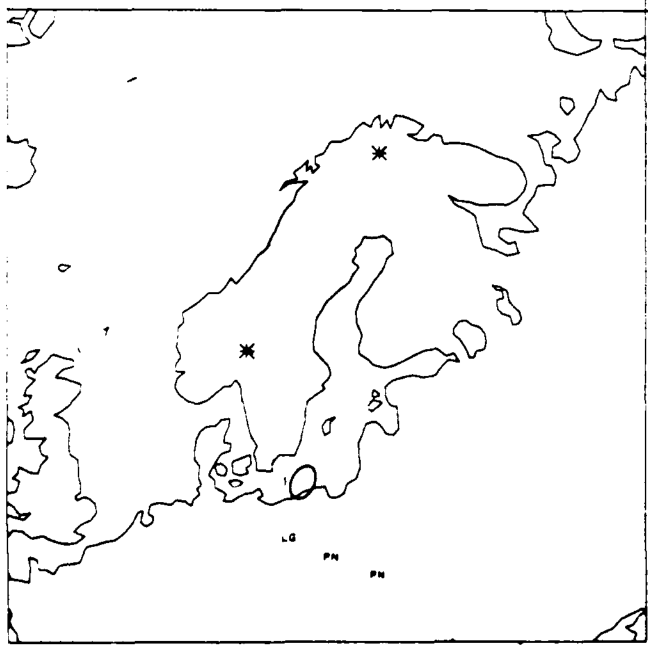
Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
P	02:14:03	1.0	285	9.0	1.8	153.3	4.6	288	5.00	1	0/0	-1
Pn	02:14:02	1.0	285	9.0	1.8	153.3	4.6	288	5.00	1	0/-3	140880
Lg	02:15:46	3.5	264	5.0	1.0	162.6	4.8	87	2.61	1	0/-1	140880

Sun Oct 29 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
[illegible]	02:16:00	3.4	279	8.5	2.1	187.1	8.7	40	3.75	2	0/0	-1
[illegible]	[illegible]	3.4	279	8.5	2.1	187.1	8.7	40	3.75	2	0/-1	140880
Pn	02:18:03	3.6	261	8.7	2.9	103.5	15.6	39	2.86	3	-1/0	138583
T	02:20:19	2.6	276	15.9	6.9	21.0	15.5	53	4.00	2	0/-3	138473
T	02:20:56	3.3	261	16.7	11.3	26.7	25.5	53	2.73	2	-1/0	38474

REALTIME RUN TUE OCT 31 10:42:23 1989





Analyst #2

MAP DIAGRAM 39.7 DEG ØRID 140880 RUN DATE 10/31/1989

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	**Wed Nov** 1 15:59:35 1989	61.87	30.77	53.3	25.7	-60.0

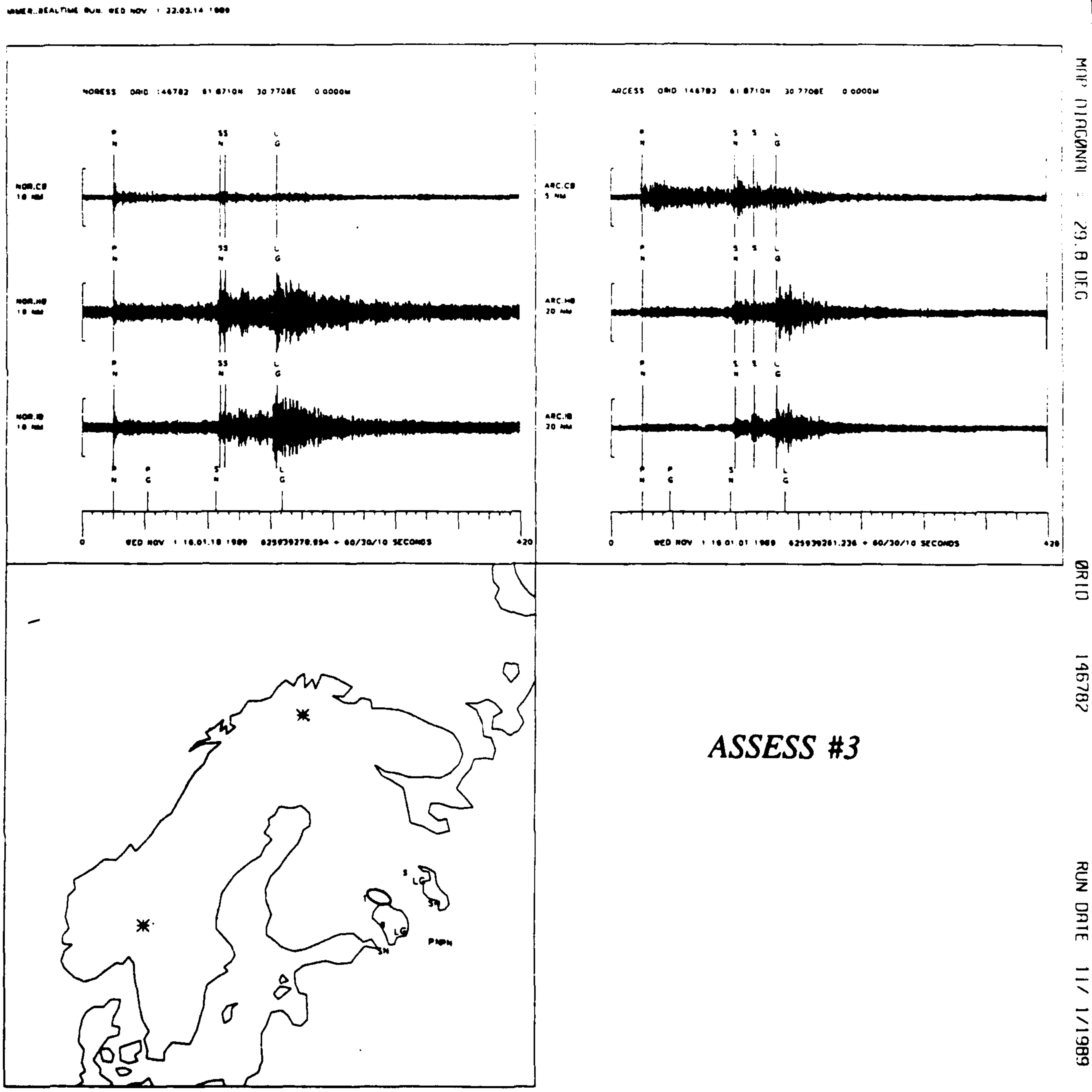
Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89/11/01 15:59 35 906	61 92	30 69	9 24	75 19	144 5	72 5	3 1
Assess(A)	89/11/01 15:59 38 352	62 05	31 23	7 92	159 93	132 7	99 6	75 2

Wed Nov 1 1989 (N)

Ph	Time	Tsd	Bms	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	16 01 48	1 0	304	12 1	5 1	95 0	9 9	370	3 16	1	1/0	146782
Sn	16 03 30	3 9	273	5 0	0 7	77.2	3 1	70	4 00	1	0/2	146782
S	16 03:35	3 7	221	4 3	0 7	70 0	7 2	468	3 00	3	0/3	146782
Lg	16.04 24	4 0	313	4 2	0 9	72 3	4 8	407	2.22	1	1/-2	146782

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bms	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	15.01 31	2 5	278	7.3	1.5	154 0	7 0	94	4 00	2	-1/-2	146782
Sn	16 03:00	3 6	221	4.8	0 8	165 5	7 3	412	3 33	3	0/1	146782
S	16 03:18	6 0	313	4.2	1.0	163 3	5 3	367	2 00	1	0/0	146782
Lg	16:03.40	3 8	313	3.6	0 5	160.0	3 2	551	2 86	1	0/-3	146782



ASSESS #3

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 15:59:34 1989	61.90	30.79	41.7	18.6	-50.9

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N	99/[illegible] 15:59:35.906	61.62	30.69	9.24	76.18	144.6	72.5	[illegible]

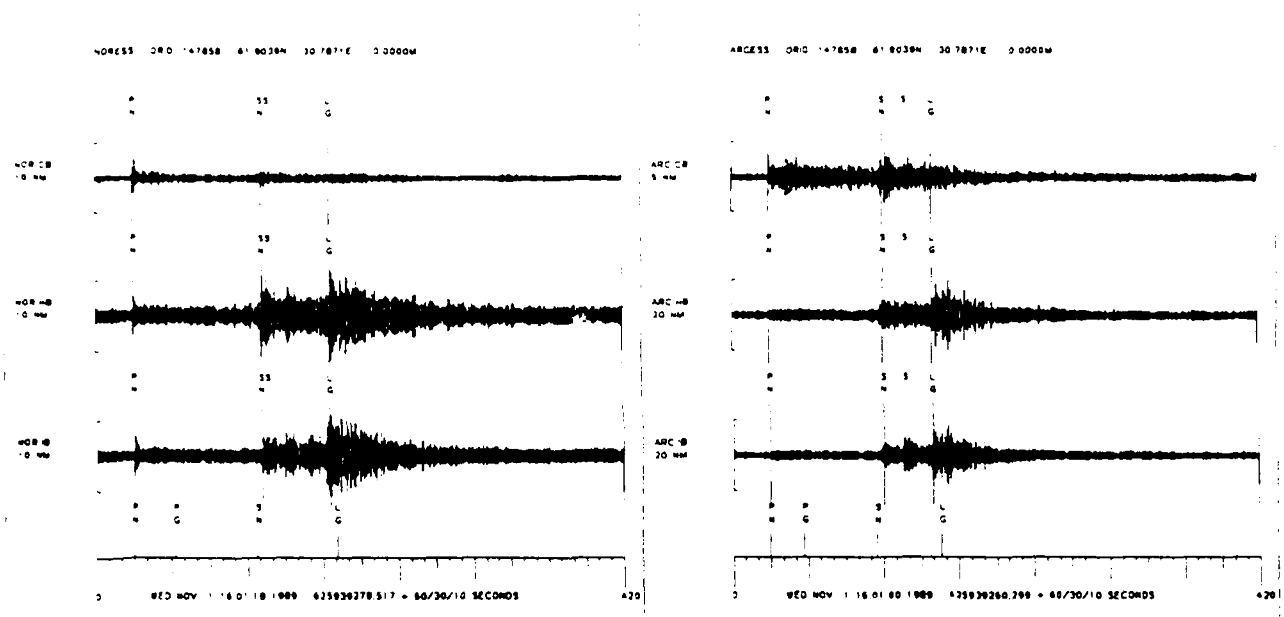
[illegible] Nov 1 1989 (N)

Ph	Time	Tsd	Bem	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
[illegible]	16 [illegible]:40	[illegible]	324	[illegible]	[illegible]	85.[illegible]	9.9	370	3.16	[illegible]	0/0	-1
Pn	16 [illegible]:48	[illegible]	324	[illegible]	[illegible]	[illegible]	[illegible]	370	3.16	[illegible]	[illegible]	147858
Sn	16 23:30	3.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.00	[illegible]	[illegible]/2	147858
S	16 23.35	[illegible]	221	4.3	[illegible]	[illegible]	[illegible]	468	3.00	3	[illegible]	147860
Lg	16 [illegible] 24	4.0	3.3	4.2	[illegible]	[illegible]	4.8	407	2.22	[illegible]	[illegible]-2	147858

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bem	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
[illegible]	16 [illegible]	2.5	278	7.3	1.5	154.0	7.0	84	4.00	2	0/0	-1
Pn	16 [illegible]30	2.5	278	7.3	1.5	154.0	7.0	84	4.00	2	-1/-2	147858
Sn	16 [illegible]	3.6	221	4.8	0.8	165.5	7.3	412	3.33	3	0/1	147858
S	16 [illegible]18	4.0	313	4.2	1.0	163.3	5.3	367	2.00	1	0/0	147859
Lg	16 [illegible]:40	3.8	313	3.6	0.5	160.0	3.2	551	2.86	1	0/-3	147858

Helsinki: 61.9N 30.6E



Analyst #3

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Tue Oct 31 19:55:03 1989	65.63	25.72	83.4	39.9	-66.6

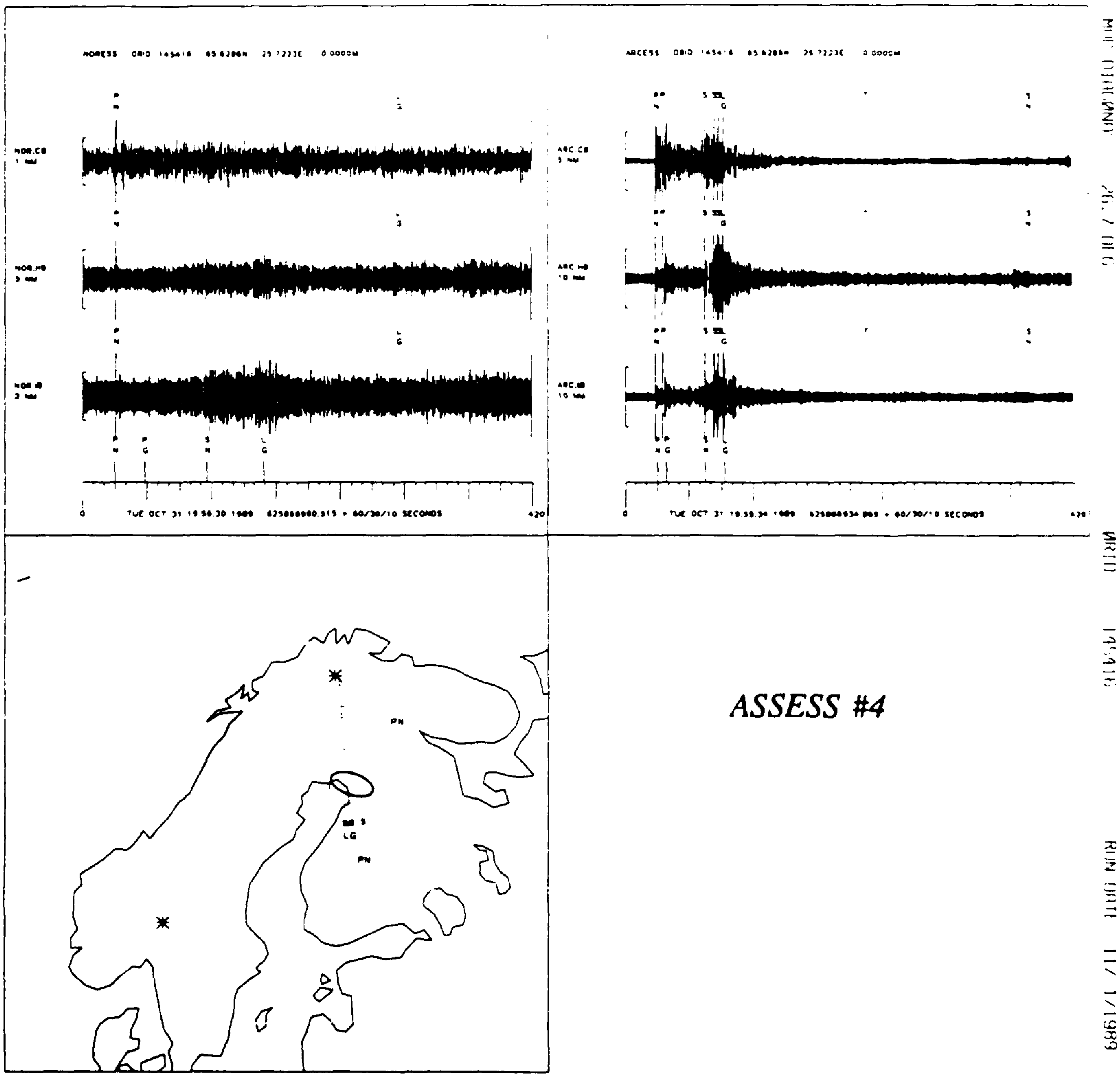
Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	59/12/31 23 59 59 000	-999 00	-999 00	27 32	19 51	1 0	1 0	1 0
Assess(A)	89/10/31 19 55 02 614	65 52	25 60	4 03	179 44	99 1	56 0	99 5

Tue Oct 31 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	19 57 01	3 1	276	9 5	2 5	41 9	5 7	54	4 29	2	0/ 1	145416
Lg	20 01 25	4 0	310	4 5	1 9	261 3	9 8	397	1 20	1	1 -3	145424

Tue Oct 31 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	19 56:03	1 7	279	7 7	1 6	177 7	4 9	94	4 00	1	0/ 3	145416
P	19 55 10	3 5	255	7 6	1 9	181 4	5 9	156	3 33	1	1 2	145416
S	19 56 49	3 9	288	4 7	0 4	175 2	3 2	104	6 00	2	0/-1	145416
S	19 56 58	3 5	303	3 9	0 5	180 4	6 3	132	3 15	3	0/3	145416
S	19 57 02	1 5	226	4 0	0 4	183 1	3 5	492	4 29	2	0/3	145416
Lg	19 57 06	3 5	226	4 7	0 6	181 5	5 5	422	4 29	3	0/2	145416
T	19 59 18	3 5	275	17 6	7 9	330 3	21 4	39	4 29	3	1/ 3	145390
Sn	20 01 52	3 9	300	2 8	0 1	259 4	1 4	44	10 00	3	0/1	145424



ASSESS #4

..te	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Tue Oct 31 19:55:04 1989	65.86	25.14	61.3	14.3	-59.1

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	59/12/31 23 59 59 000	999 00	999 00	17 32	19 6	[illegible]	[illegible]	[illegible]

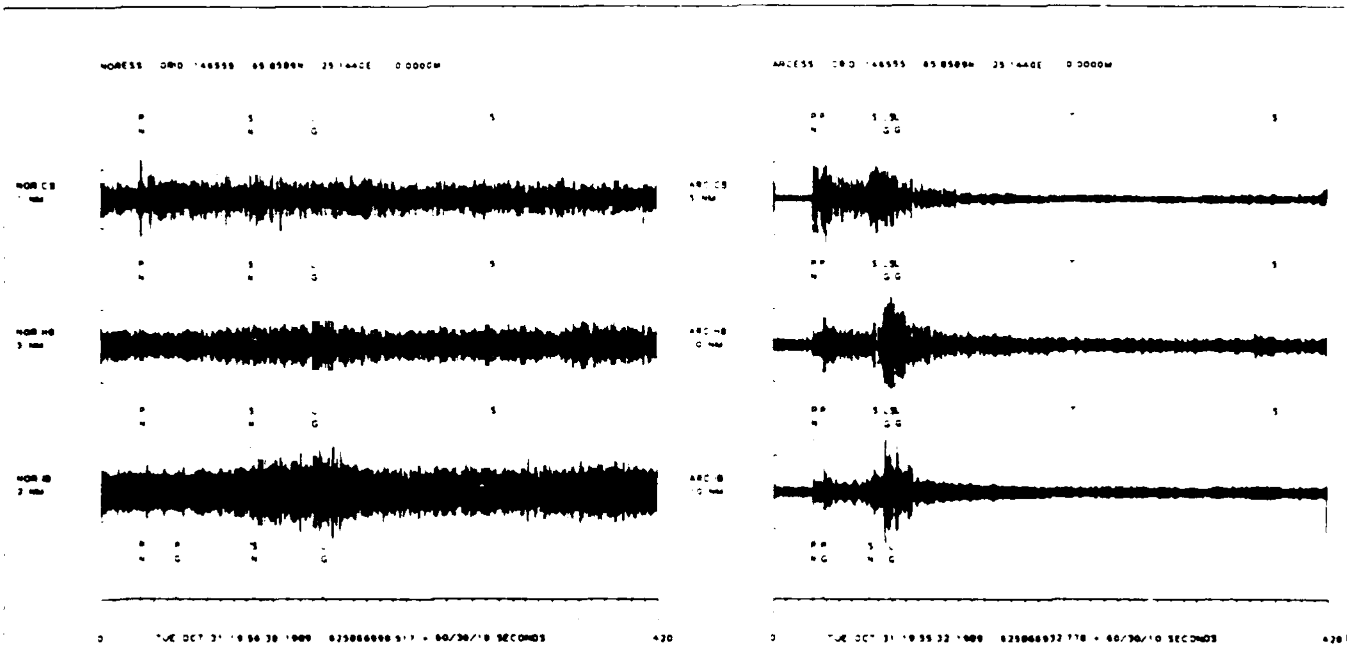
Tue Oct 31 1989 (N)

Ph	Time	Tsd Bmo	Vel	Dvel	Azim	Aed	Stavg	Freq	Fkq	P/Sp	Orid
[illegible]	19 57 01	3 1 274	9 9	2 5	41 9	9 7	54	4 29	2	2 [illegible]	[illegible]
Pn	19 57 00	3 1 276	9 9	2 5	41 9	9 7	54	4 29	2	2 1	146555
Sn	19 58 22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	[illegible]	146555
Lg	19 59 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	[illegible]	146555
S	20 01 25	4 0 310	4 5	1 9	241 3	9 9	397	1 20	1	1 1	146553

Tue Oct 31 1989 (A)

Ph	Time	Tsd Bmo	Vel	Dvel	Azim	Aed	Stavg	Freq	Fkq	P/Sp	Orid
[illegible]	19 56 03	1 7 279	7 7	1 6	177 7	4 9	84	4 20	1	2 0	[illegible]
Pn	19 56 03	1 7 279	7 7	1 6	177 7	4 9	84	4 20	1	2 1	146555
P	19 55 10	3 5 265	7 6	1 9	181 4	5 9	155	3 33	1	[illegible]	146556
S	19 56 49	3 9 288	4 7	0 4	176 2	3 0	124	6 30	2	3 1	146557
Lg	19 56 58	3 5 303	3 9	0 5	180 4	6 3	132	3 16	1	3 3	146555
S	19 57 02	1 6 226	4 0	0 4	193 1	3 5	492	4 29	2	3 3	146558
Lg	19 57 05	3 5 226	4 7	0 5	181 5	5 5	422	4 [illegible]	3	[illegible]	146559

Helsinki: 65.8N 24.7E



Analyst #4

RUN DATE 11/ 1/1989

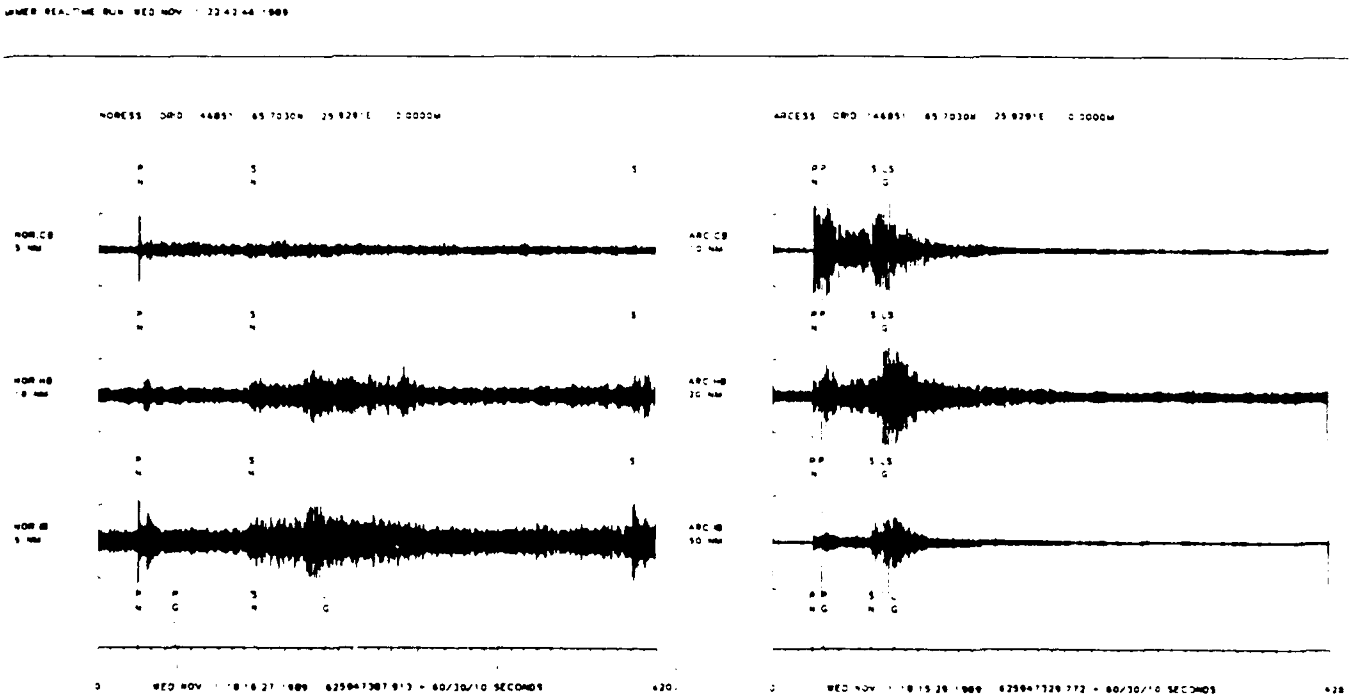
Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 18:14:59 1989	65.70	25.93	58.5	23.3	-60.4

Wed Nov 1 1989 (N)

Ph	Time	Tsd	Bms	Vel	Dvel	Azim	Aed	Stavg	Freq	Fkq	P	Sp	Orid
Pn	18 16 57	1.2	309	9.9	[illegible]	61.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sn	[illegible]	[illegible]	226	4.2	[illegible]	[illegible]	5.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
S	[illegible]	[illegible]	259	[illegible]	[illegible]	69.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bms	Vel	Dvel	Azim	Aed	Stavg	Freq	Fkq	P	Sp	Orid
Pn	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
P	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.9	85	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
S	[illegible]	[illegible]	[illegible]	4.8	[illegible]	182.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Lg	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
S	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	187.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



ASSESS #5

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 18:14:59 1989	65.71	25.54	48.4	16.9	-58.0

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89 [illegible] 18:15:04.775	64.72	26.15	[illegible]	52.87	232.6	166.9	-24.0

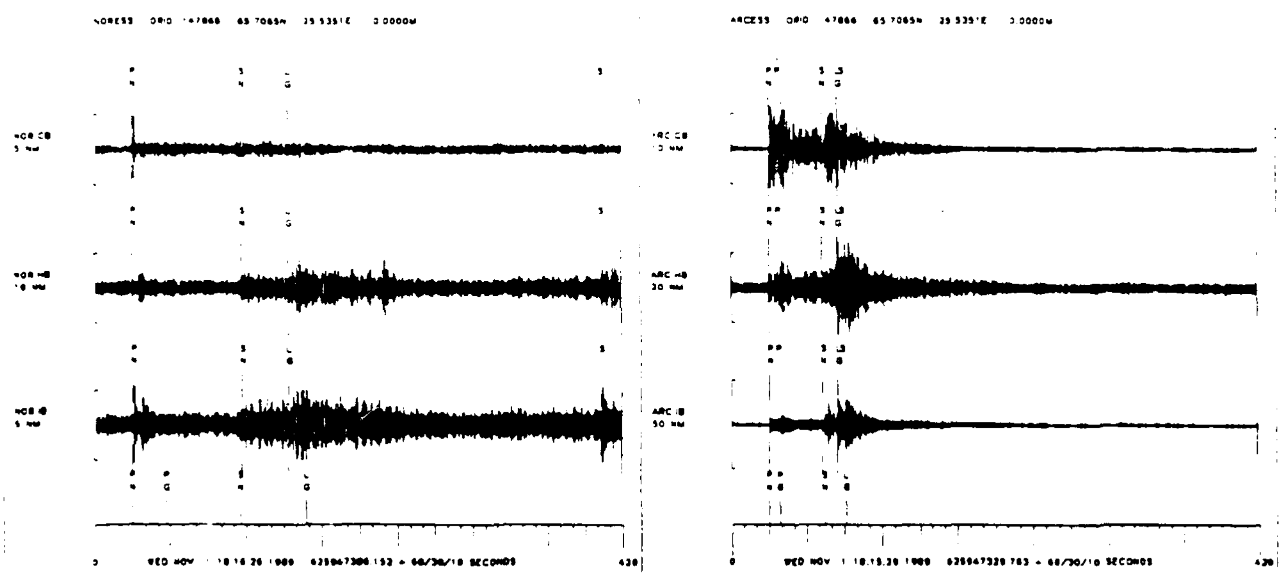
[illegible] Nov [illegible] 1989 (N)

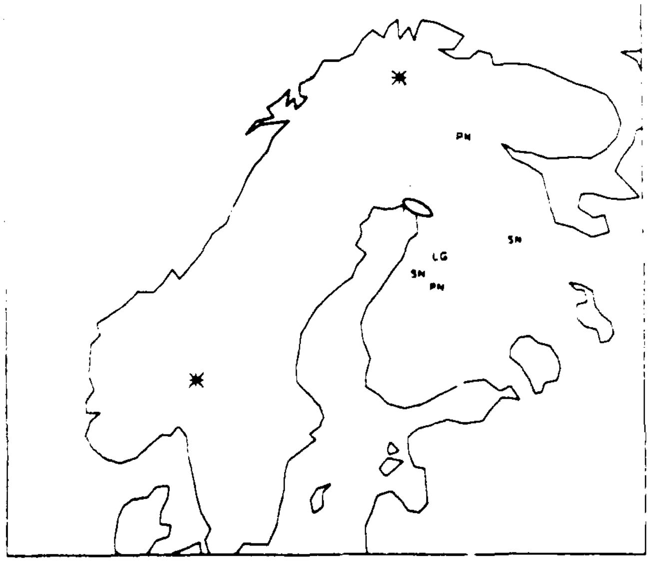
	Time	Tsd	Bmr	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
[illegible]	18:16:57	[illegible]	339	8.9	2.5	41.2	6.4	200	3.53	1	0/0	-1
P-	18:16:56	[illegible]	339	9.9	2.5	41.2	6.4	200	3.53	1	0 -3	147866
S-	18:18:22	3.[illegible]	226	4.2	[illegible]	[illegible]	[illegible]	192	4.29	3	0.2	147866
Lg	18:19:00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1	-1.00	-1	0/0	147866
S	18:23:39	3.0	259	2.9	2.4	68.5	3.1	121	2.31	1	0 -3	146832

Wed Nov 1 1989 (A)

P-	Time	Tsd	Bmr	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
[illegible]	18:16:00	1.2	285	7.8	[illegible]	177.5	3.3	251	6.00	1	0/0	-1
P-	18:16:00	1.2	285	7.8	[illegible]	177.5	3.3	251	6.00	1	[illegible]-3	147866
P	18:16:06	3.[illegible]	273	7.5	1.6	176.4	4.0	86	4.00	1	[illegible]-2	147867
Sn	18:16:42	3.4	313	4.8	0.8	182.4	4.1	683	3.00	1	0/-1	147866
[illegible]	18:16:44	3.4	313	4.8	0.8	182.4	4.1	683	3.00	1	0/0	-1
[illegible]	18:16:53	3.2	221	3.7	0.4	175.0	2.8	1706	3.33	1	0/0	-1
Lg	18:16:55	3.2	221	3.7	0.4	175.0	2.8	1706	3.33	1	1/0	147866

[illegible] REALTIME RUN THU NOV 2 18:07:38 1989





Analyst #5

MAP DIAGRAM 26.1 DEG ORID 147866 RUN DATE 11/ 2/1989

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Thu Nov 2 12:14:36 1989	59.70	26.82	175.8	46.3	-10.5

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89/11/02 12 14 38 183	59 42	26 53	7 58	93 42	319 2	111 5	15 6
Assess(A)	59/12/31 23 59 59 000	-999 00	-999 00	15 99	26 17	-1 0	-1 0	-1 0

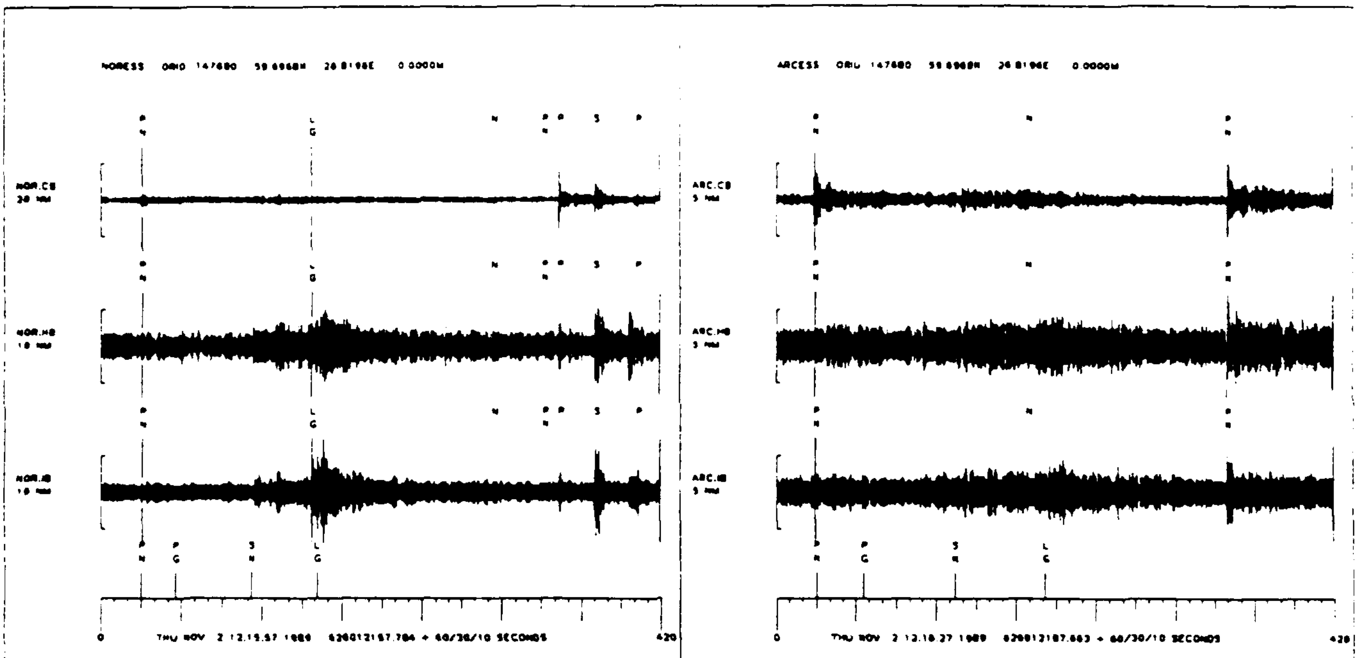
Thu Nov 2 1989 (N)

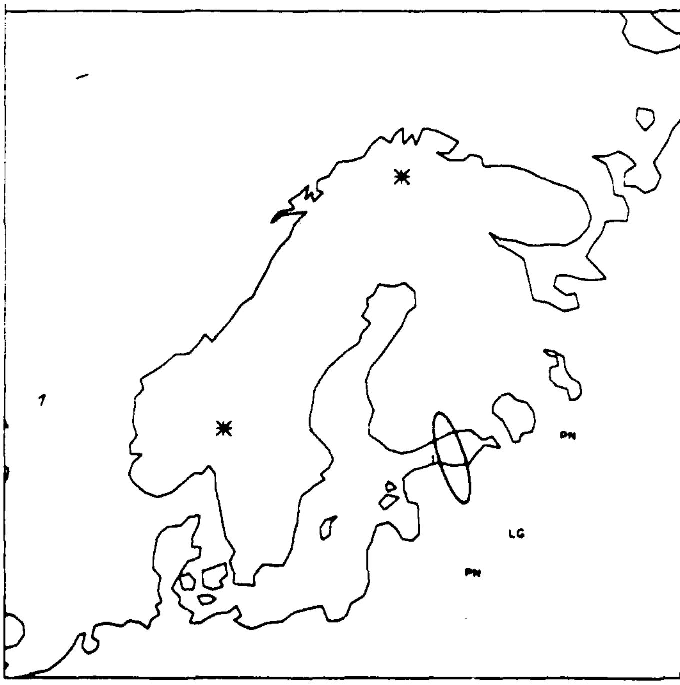
Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12 15 28	4 0	284	9 5	1 7	94 7	9 1	131	5 00	3	0/-1	147680
Lg	12 18 35	2 7	310	4 2	1 5	103 6	8 6	967	1 28	1	1/-3	147580
N	12 20 52	3 9	280	2 7	0 2	113 9	3 2	80	4 29	3	0/-1	147511
Pn	12.21.30	3 6	298	7 4	0 9	101 4	2 8	121	5 67	1	0/-1	147571
P	12 21 41	1 8	284	7 3	0 9	100 8	2 8	377	5 57	1	0/-3	147513
S	12 22.08	2 2	272	4 0	0 5	107 0	4 1	204	3 75	2	0/-2	147514
P	12.22 40	3 3	263	9 9	3.4	77 2	16 1	223	3 16	3	0/-3	147515

Thu Nov 2 1989 (A)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12.16.56	2 8	285	8 8	1.6	175 8	4 1	101	5 45	1	0/-3	147680
N	12 19 3.	3 9	296	3 0	0 2	226 8	3 7	98	5 00	4	0/-3	147505
Pn	12 22:06	1 3	264	5 9	1 5	147 4	5 0	215	3 53	1	0/-3	147571

NMER..REALTIME RUN THU NOV 2 09.58.44 1989





ASSESS #6

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Thu Nov 2 12:14:33 1989	59.56	27.02	45.3	21.0	-38.8

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess.N	89 11 02 12:14:38.183	59.42	26.53	7.58	93.42	319.2	111.5	16.6

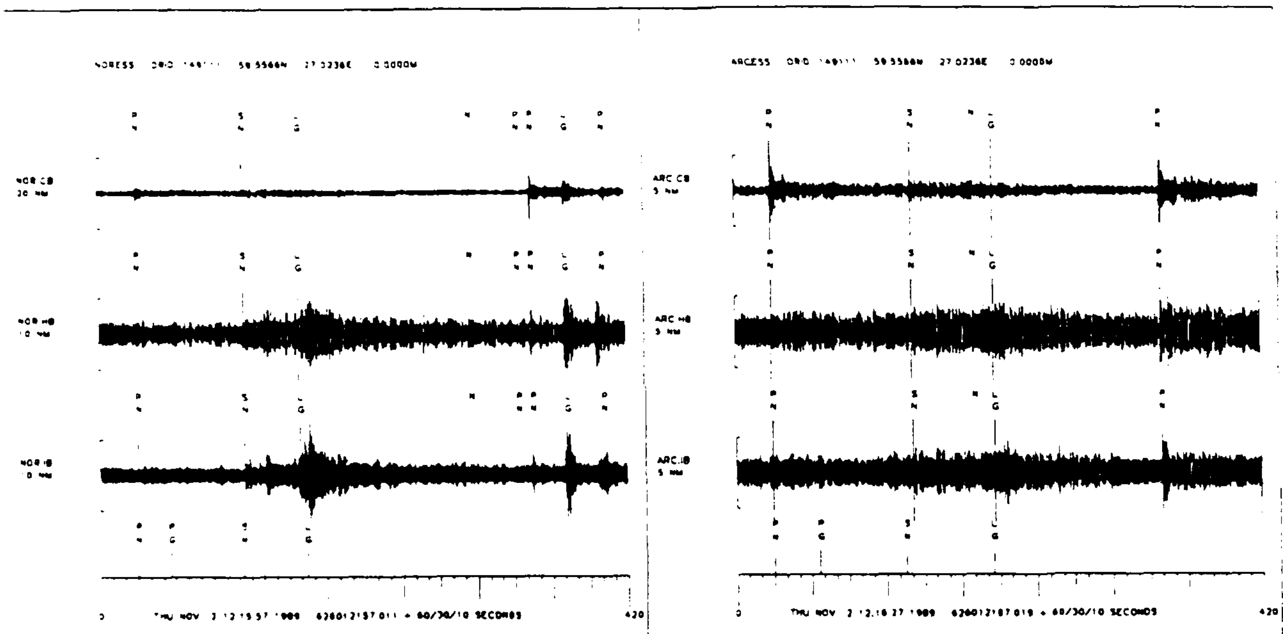
Thu Nov 2 1989 (N)

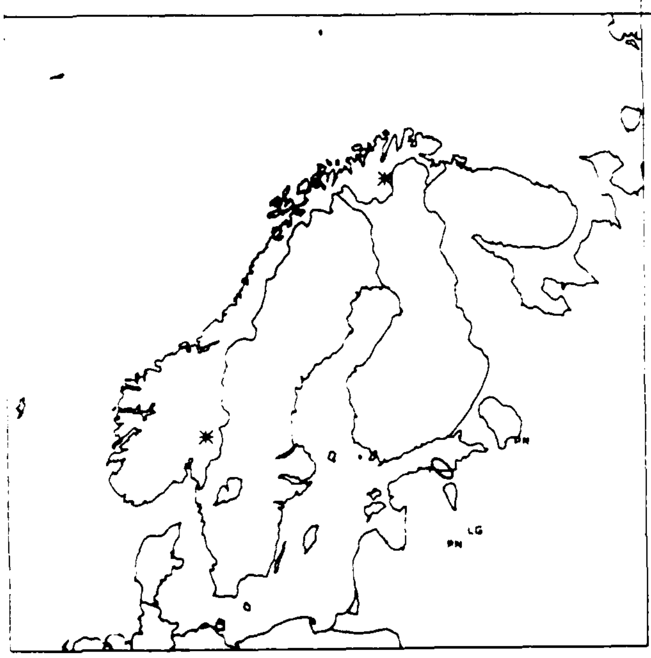
Ph	Time	Tsd	Snr	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:16:27	4.1	284	9.5	1.7	84.7	8.1	131	6.00	3	0/-1	149111
[illegible]	12:16:28	4.0	284	9.5	1.7	84.7	8.1	131	6.00	3	0/0	-1
Sn	12:17:51	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	149111
[illegible]	12:18:35	2.7	310	4.2	1.6	103.6	8.6	967	1.28	1	0/0	-1
Lg	12:18:36	2.7	310	4.2	1.6	103.6	8.6	967	1.28	1	1/-3	149111
N	12:20:52	3.9	290	2.7	2.2	113.9	3.2	80	4.29	3	0/-1	147611
Pn	12:21:30	3.6	298	7.4	0.9	111.4	2.8	121	6.67	1	0/-1	149115
[illegible]	12:21:41	1.8	284	7.3	0.9	100.8	2.8	377	6.67	1	0/0	-1
Pn	12:21:41	1.8	284	7.3	0.9	100.8	2.8	377	6.67	1	0/-3	149116
Lg	12:22:08	2.2	272	4.0	0.5	107.0	4.1	204	3.75	2	0/-2	149116
Pn	12:22:30	3.3	263	9.9	3.4	77.2	16.1	223	3.16	3	0/-3	149114
[illegible]	12:22:40	3.3	263	9.9	3.4	77.2	16.1	223	3.16	3	0/0	-1

Thu Nov 2 1989 (A)

Ph	Time	Tsd	Snr	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:16:56	2.0	285	8.0	1.6	175.8	4.1	131	5.45	1	0/-3	149111
Sn	12:18:48	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	149111
N	12:19:37	3.9	296	3.0	0.2	226.8	3.7	80	5.00	4	0/-3	147605
Lg	12:19:52	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	149111
Pn	12:22:06	1.3	264	6.9	1.5	147.4	5.0	215	3.53	1	-1/-3	149114

Helsinki: 59.3N 27.2E





Analyst #6

MAP DIMENSION - 30.0 DEG ØRID 149111 RUN DATE 11/ 5/1989

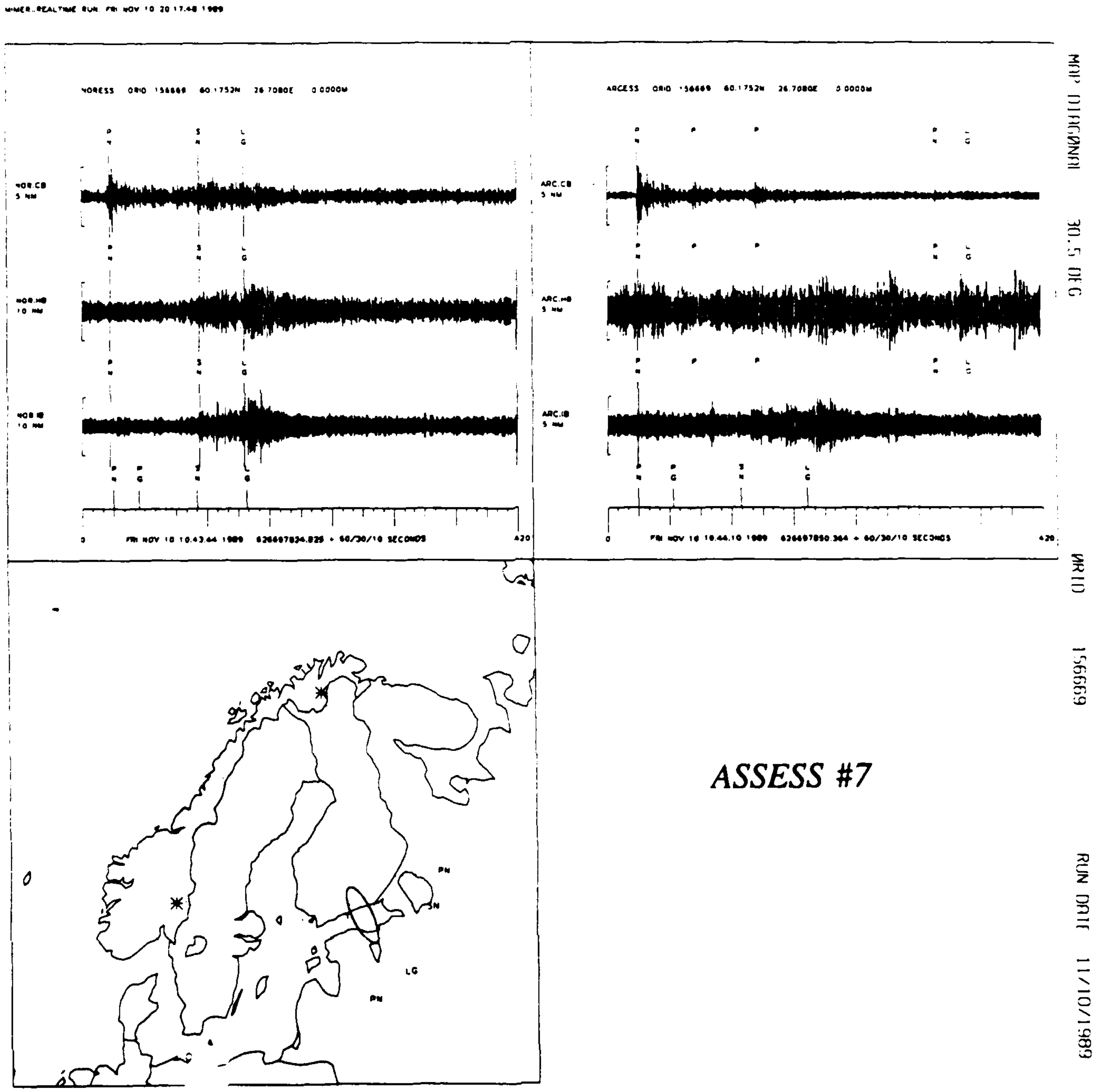
Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Fri Nov 10 10:42:25 1989	60.18	26.71	138.2	43.4	-19.0

Fri Nov 10 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
P	10:44:11	3.6	291	11.1	2.0	76.7	6.3	161	6.67	2	1/-3	156669
	10:45:37	4.0	226	4.8	0.5	84.4	5.2	265	4.62	3	0/0	156669
	10:46:20	3.7	310	4.5	1.8	100.2	9.3	661	1.25	1	0/-3	156669

Fri Nov 10 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	10:44:40	2.3	285	8.9	1.6	176.4	4.1	159	5.45	1	0/-3	156669
P	10:45:34	3.7	271	8.8	2.1	149.2	11.2	73	4.00	3	0/-3	156629
P	10:46:35	4.0	201	6.1	3.3	349.3	13.3	361	1.22	1	0/0	56633
Pn	10:49:27	2.6	291	7.6	1.0	90.9	3.2	133	6.00	1	0/-1	[illegible]6659
Lg	10:43:59	3.8	225	4.0	0.3	94.7	3.0	145	5.00	2	0/-2	[illegible]6659



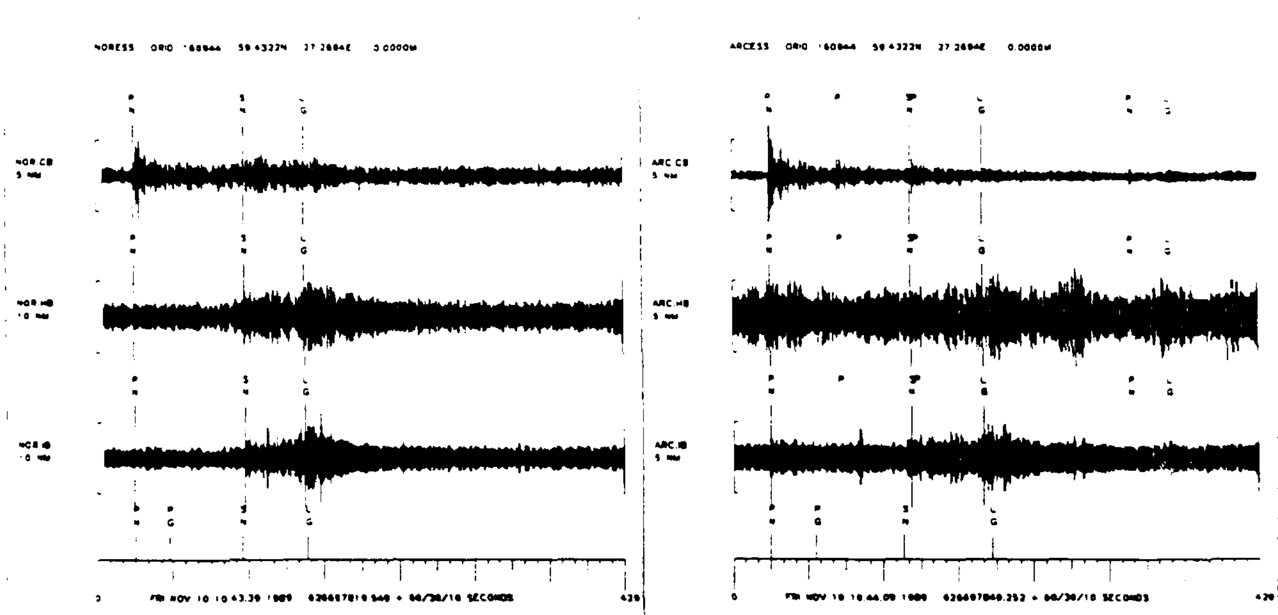
Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Fri Nov 10 10:42:14 1989	59.43	27.27	48.9	23.3	-38.9

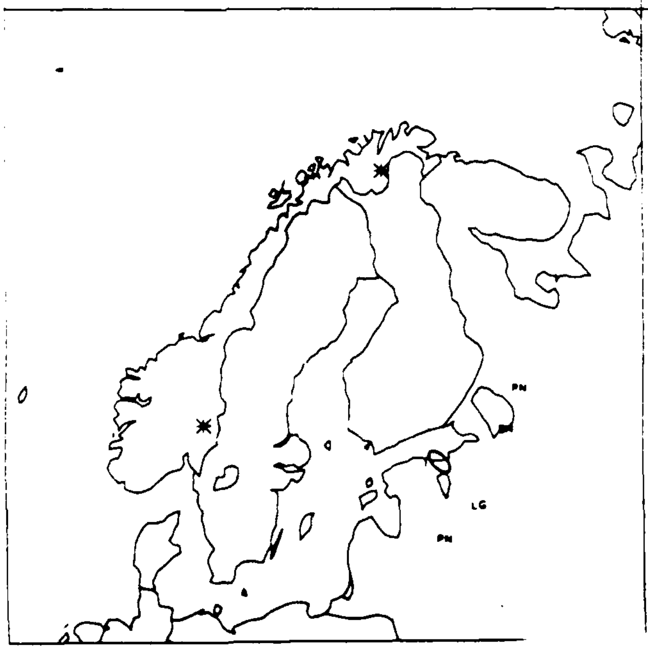
Fri Nov 10 1989 (N)

Ph	Time	Tsd	Smn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	10:44:09	3.6	291	11.1	2.0	76.7	6.3	161	6.67	2	1/-3	160944
??	10:44:11	3.6	291	11.1	2.0	76.7	6.3	161	6.67	2	0/0	-1
Sn	10:45:36	4.0	226	4.8	0.5	84.4	5.2	265	4.62	3	0/0	160944
??	10:45:37	4.0	226	4.8	0.5	84.4	5.2	265	4.62	3	0/0	-1
??	10:46:20	3.7	310	4.5	1.8	100.2	9.3	661	1.25	1	0/0	-1
Lg	10:46:24	3.7	310	4.5	1.8	100.2	9.3	661	1.25	1	0/-3	160944

Fri Nov 10 1989 (A)

Ph	Time	Tsd	Smn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	10:44:39	2.3	285	8.9	1.6	176.4	4.1	159	5.45	1	0/-3	160944
??	10:44:40	2.3	285	8.9	1.6	176.4	4.1	159	5.45	1	0/0	-1
P	10:45:34	3.7	271	8.8	2.1	149.2	11.2	73	4.00	3	0/-3	156629
Sn	10:46:31	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	160944
P	10:46:35	4.0	201	6.1	3.3	349.3	13.3	361	1.22	1	0/0	156633
Lg	10:47:28	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	160944
Pn	10:49:26	2.6	291	7.6	1.0	90.9	3.2	133	6.00	1	0/-1	161035
??	10:49:27	2.6	291	7.6	1.0	90.9	3.2	133	6.00	1	0/0	-1
Lg	10:49:57	3.8	225	4.0	0.3	94.7	3.0	145	5.00	2	0/-2	161035





Analyst #7

MAP DIAGRAM 30.5 DEG ØRID 160944 RUN DATE 11/14/1989

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Thu Nov 16 12:24:05 1989	58.50	18.52	71.8	41.9	-18.4

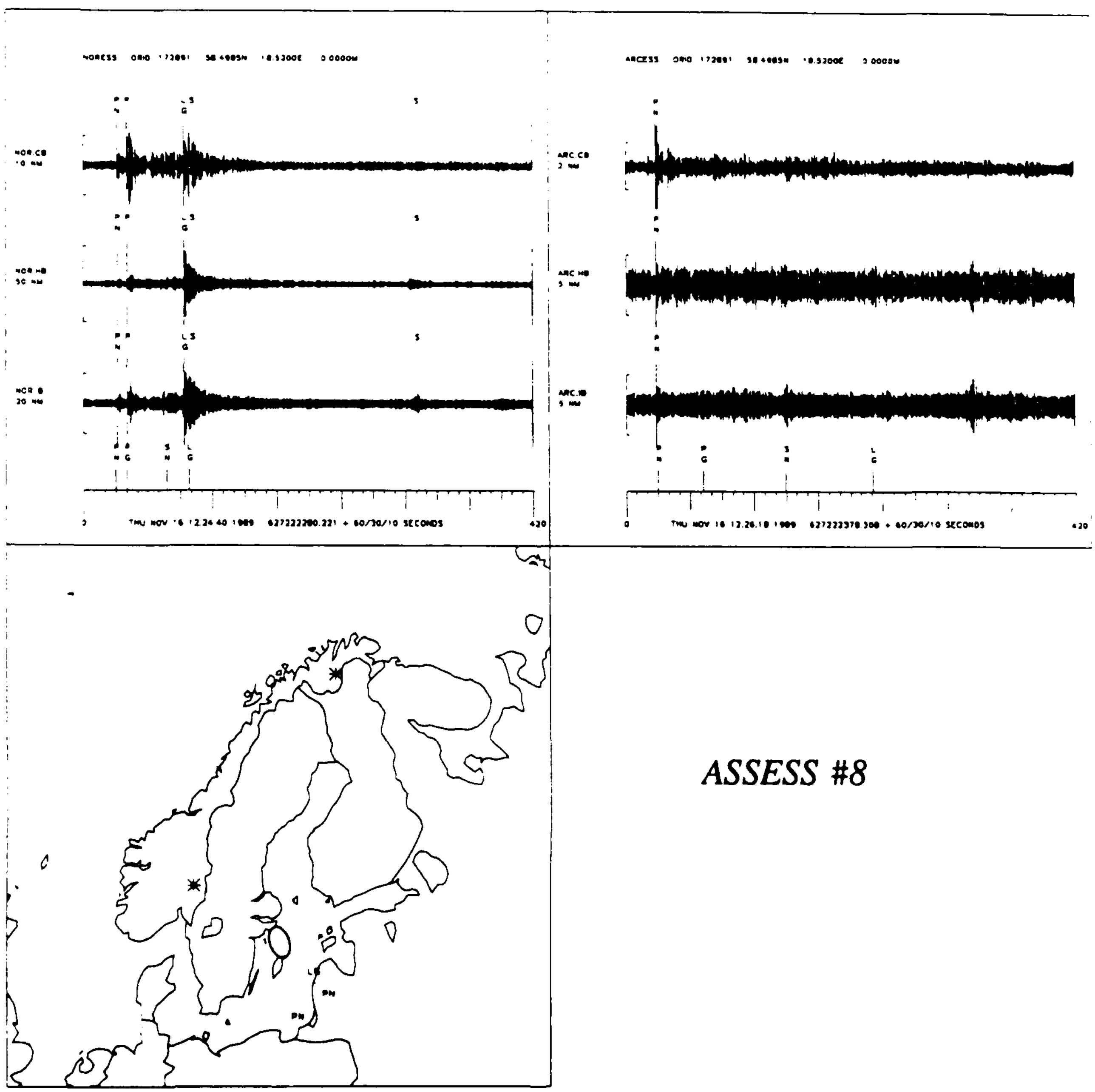
Thu Nov 16 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:25:11	1.6	277	9.5	2.7	124.1	6.5	356	3.75	1	-1/0	172891
P	12:25:21	3.0	266	9.2	2.5	107.5	6.2	203	3.75	1	-1/-3	172891
Lg	12:26:13	3.4	280	3.9	0.4	121.0	2.5	343	4.00	1	-1/0	172891
S	12:26:20	1.3	301	4.4	0.2	134.8	2.6	393	0.57	3	0/-1	172817
S	12:29:51	3.4	220	3.9	1.0	183.4	5.7	472	1.76	1	0/-3	172820

Thu Nov 16 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:26:46	1.9	279	7.8	1.7	193.1	4.9	123	4.00	1	0/-3	172891

MINER REALTIME RUN, SAT NOV 18 03:50:41 1989



MAP DIAGRAM 31.7 DEG ORID 172891 RUN DATE 11/18/1989

Site Assess:	Origin Time	Lat	Lon	SMaj	SMin	Strike
	Thu Nov 16 12:24:06 1989	58.66	18.74	54.4	22.2	-18.8

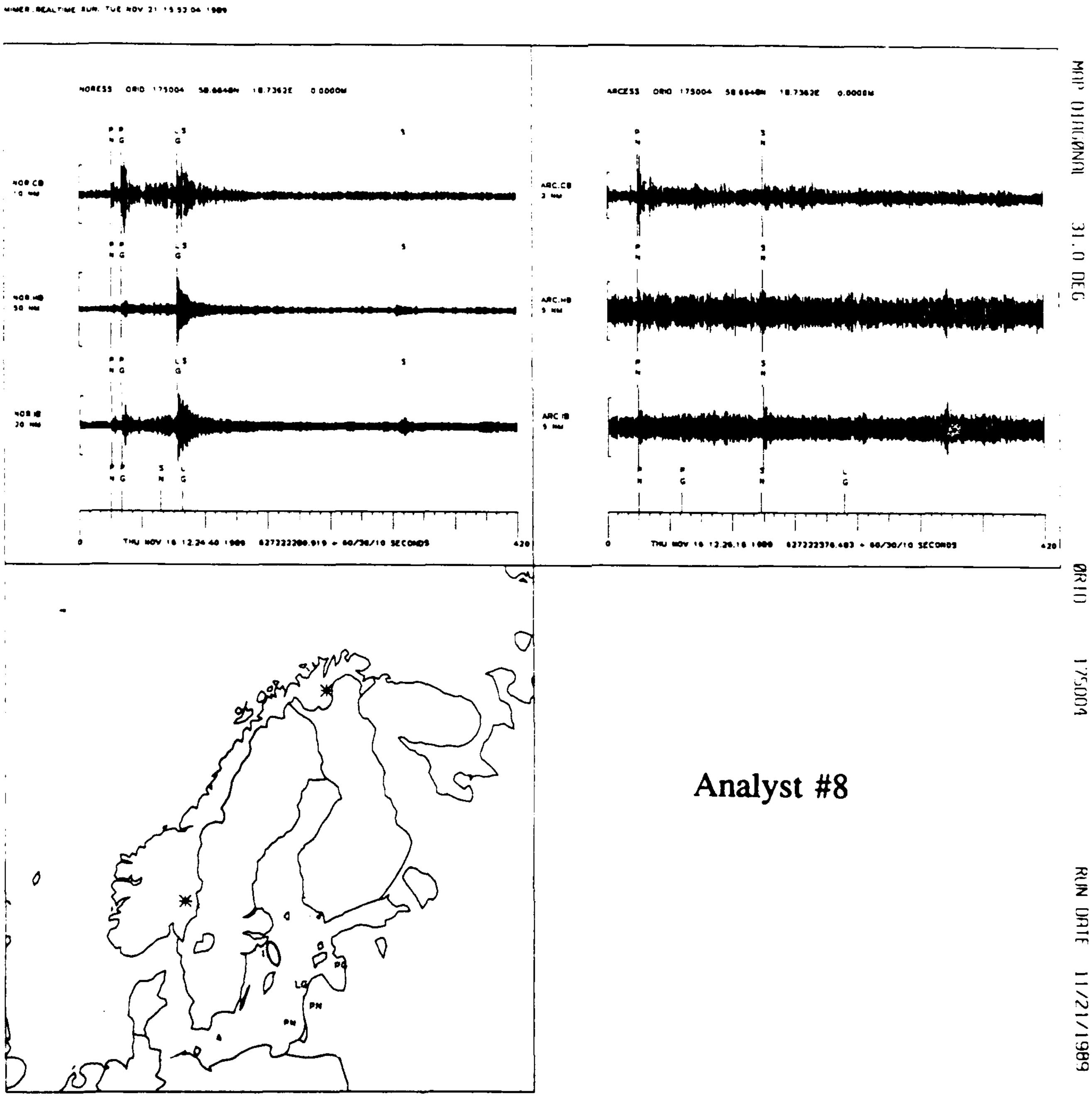
Thu Nov 16 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:25:11	1.6	277	9.5	2.7	124.1	6.5	356	3.75	1	-1/0	175004
Pg	12:25:21	3.0	266	9.2	2.5	107.5	6.2	203	3.75	1	-1/-3	175004
Lg	12:26:14	3.4	280	3.9	0.4	121.0	2.5	343	4.00	1	-1/0	175004
S	12:26:20	1.3	301	4.4	0.2	134.8	2.6	393	0.57	3	0/-1	172817
S	12:29:51	3.4	220	3.9	1.0	183.4	5.7	472	1.76	1	0/-3	172820

Thu Nov 16 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:26:46	1.9	279	7.8	1.7	193.1	4.9	123	4.00	1	0/-3	175004
Sn	12:20:45	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	175004

Helsinki: 58.996N 18.1768E



Analyst #8

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 12:25:25 1989	58.54	31.25	166.6	90.9	-54.3

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89/11/01 12:24:43.782	57.34	35.70	12.50	94.55	247.0	152.2	25.5
Assess(A):	89/11/01 12:25:40.823	59.08	27.32	10.49	174.89	200.7	103.0	86.5

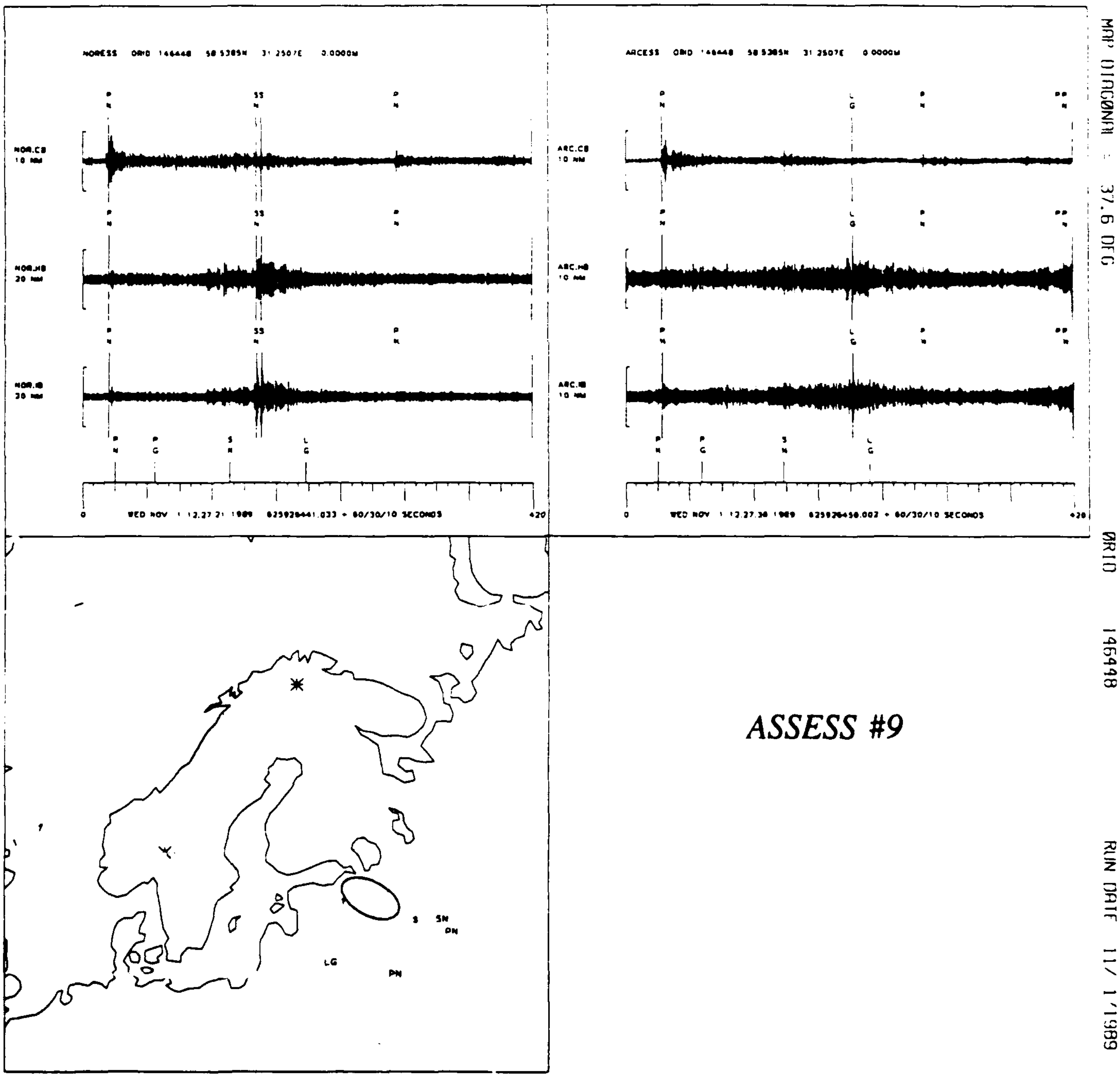
Wed Nov 1 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:27:44	1.5	249	7.9	2.4	95.6	14.2	479	2.55	3	0/-3	145448
Sn	12:30:01	3.9	221	3.9	0.5	94.5	3.0	572	3.33	1	1/-3	145448
S	12:30:07	3.9	258	3.7	0.5	95.3	3.1	268	3.30	1	1/-1	145448
Pn	12:32:13	3.9	249	8.6	3.2	103.2	17.1	127	2.61	3	0/-1	145449

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:28:10	2.2	279	8.0	1.4	164.5	8.1	122	5.00	3	0/-3	145448
Lg	12:31:08	4.0	312	3.3	0.4	176.2	2.9	417	2.85	1	0/-3	146448
Pn	12:32:13	3.9	278	8.7	2.1	164.4	11.1	75	4.00	3	0/-2	145449
P	12:34:21	2.8	201	12.9	14.1	64.8	-30.0	602	1.30	2	0/0	145302
Pn	12:34:27	3.9	248	13.6	11.1	35.2	33.0	345	1.52	2	0/-1	145446

NMER_REALTIME RUN. WED NOV 1 11.56.56 1989



Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 12:25:41 1989	59.16	28.09	41.7	21.1	-38.8

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N):	89/11/01 12.24:43.782	57.34	35.70	12.80	94.65	247.0	162.2	25.5

d Nov 1 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:27:43	1.8	249	7.9	2.4	96.6	14.2	479	2.86	3	0/-3	147829
""	12:27:44	1.8	249	7.9	2.4	96.6	14.2	479	2.86	3	0/0	-1
Sn	12:29:16	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	147829
""	12:30:01	3.9	221	3.9	0.5	94.6	3.0	672	3.33	1	0/0	-1
Lg	12:30:02	3.9	221	3.9	0.5	94.6	3.0	672	3.33	1	1/-3	147829
S	12:30:37	3.9	258	3.7	0.5	96.3	3.1	268	3.00	1	1/-1	147830
""	12:32:13	3.9	249	8.6	3.2	103.2	17.1	127	2.61	3	0/0	-1
Pn	12:32:12	3.9	249	8.6	3.2	103.2	17.1	127	2.61	3	0/-1	147831

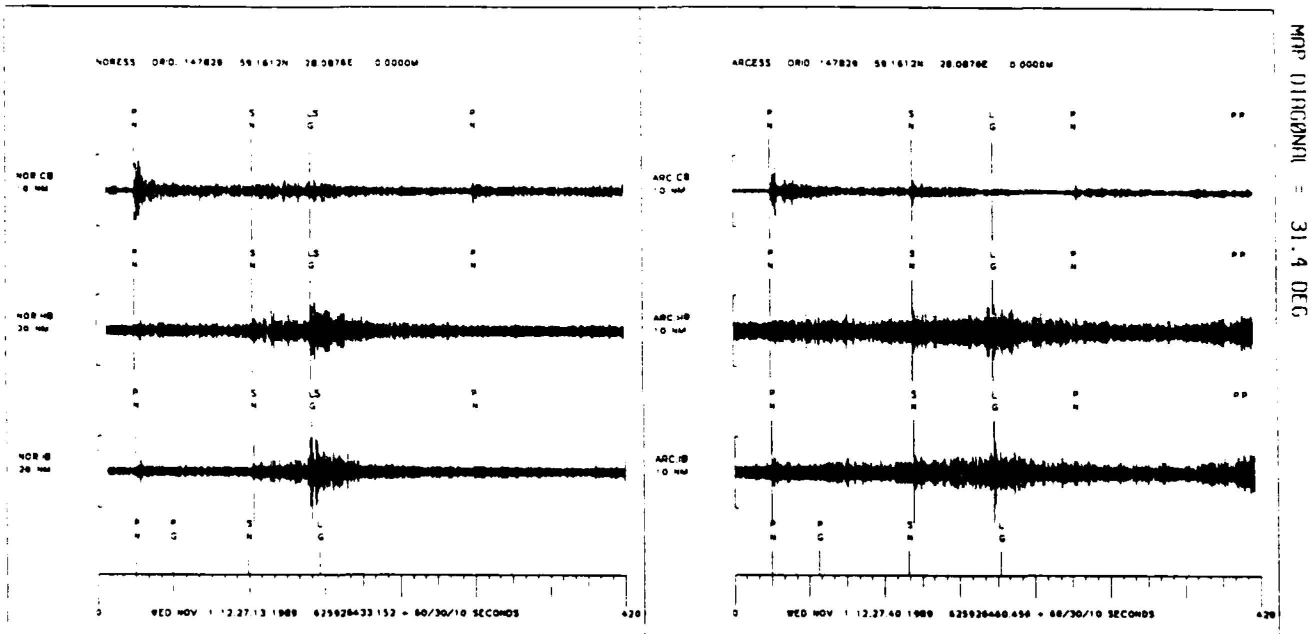
P	12:34:21	2.8	201	12.9	14.1	64.8	-30.0	602	1.30	2	0/0	146302
P	12:34:27	3.9	248	13.6	11.1	35.2	33.0	345	1.82	2	0/-1	147832

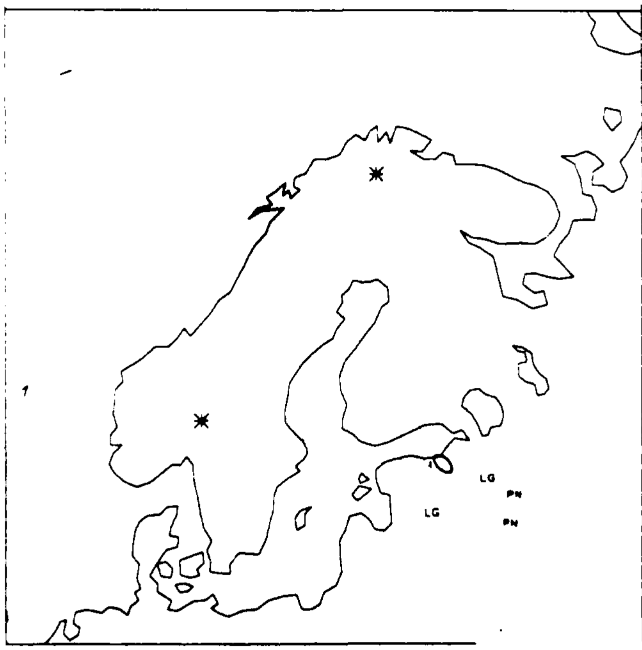
Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:28:10	2.2	279	8.0	1.4	164.5	8.1	122	5.00	3	0/-3	147829
Sn	12:30:03	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	147829
Lg	12:31:08	4.0	312	3.3	0.4	176.2	2.9	417	2.86	1	0/-3	147829
Pn	12:32:12	3.9	278	8.7	2.1	164.4	11.1	75	4.00	3	0/-2	147831

Helsinki: 59.2N 27.6E

NMMER.REALTIME RUN THU NOV 2 17.38.29 1989





Analyst #9

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 13:02:45 1989	58.71	29.74	155.0	73.8	-50.0

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89/11/01 13:02.55 649	60 04	29 02	9 54	85 97	261 7	157 3	12 3
Assess(A)	89/11/01 13:02 00.765	56 49	30 06	13 19	168 94	233 1	199 3	83 0

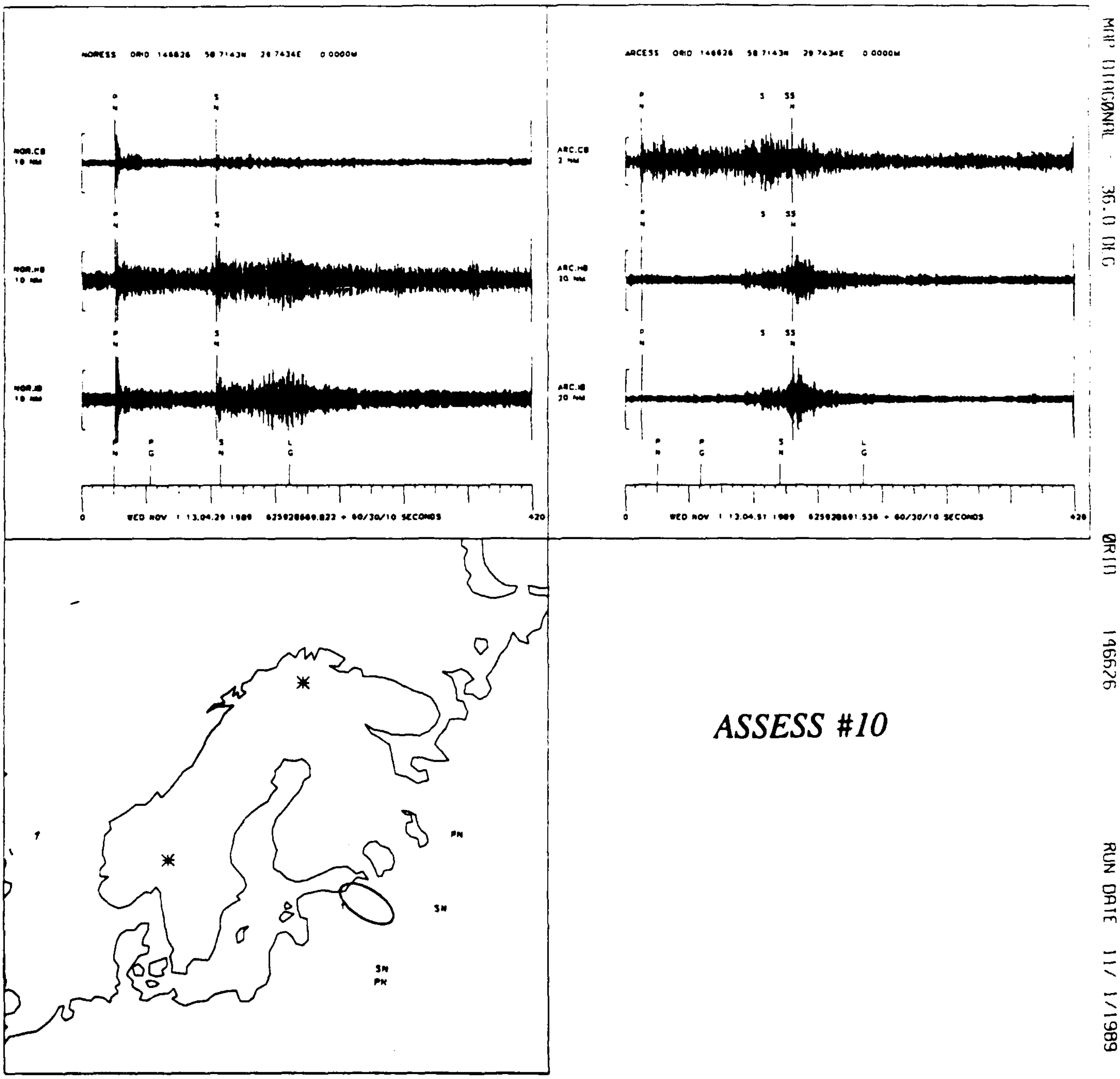
Wed Nov 1 1989 (N)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	13 05 00	1 0	305	11 6	3 7	75 4	7 5	492	4 00	1	0/-1	146626
Sn	13 06 34	3 9	221	3 3	0 4	91 9	5.0	429	3 33	3	0/1	146626

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Smo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	13.05.06	3 9	264	8 0	2.3	169 7	13 0	53	3 16	3	0/-1	146626
S	13 06:59	3 9	313	4 5	1 0	170 4	5 1	312	2 22	1	0/0	146579
S	13:07.22	4 0	220	4.0	0 9	159 3	5 5	604	1 82	1	0/-1	146580
Sn	13:07 27	3 6	221	3 4	0 4	168 9	2 7	923	3 15	1	0/-1	146626

REALTIME RUN: WED NOV 1 20.14.05 1989



ASSESS #10

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 13:02:59 1989	60.93	28.98	49.2	21.5	-45.4

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N):	89/11/01 13:02:55.649	60.04	29.02	8.64	86.97	261.7	157.9	12.3

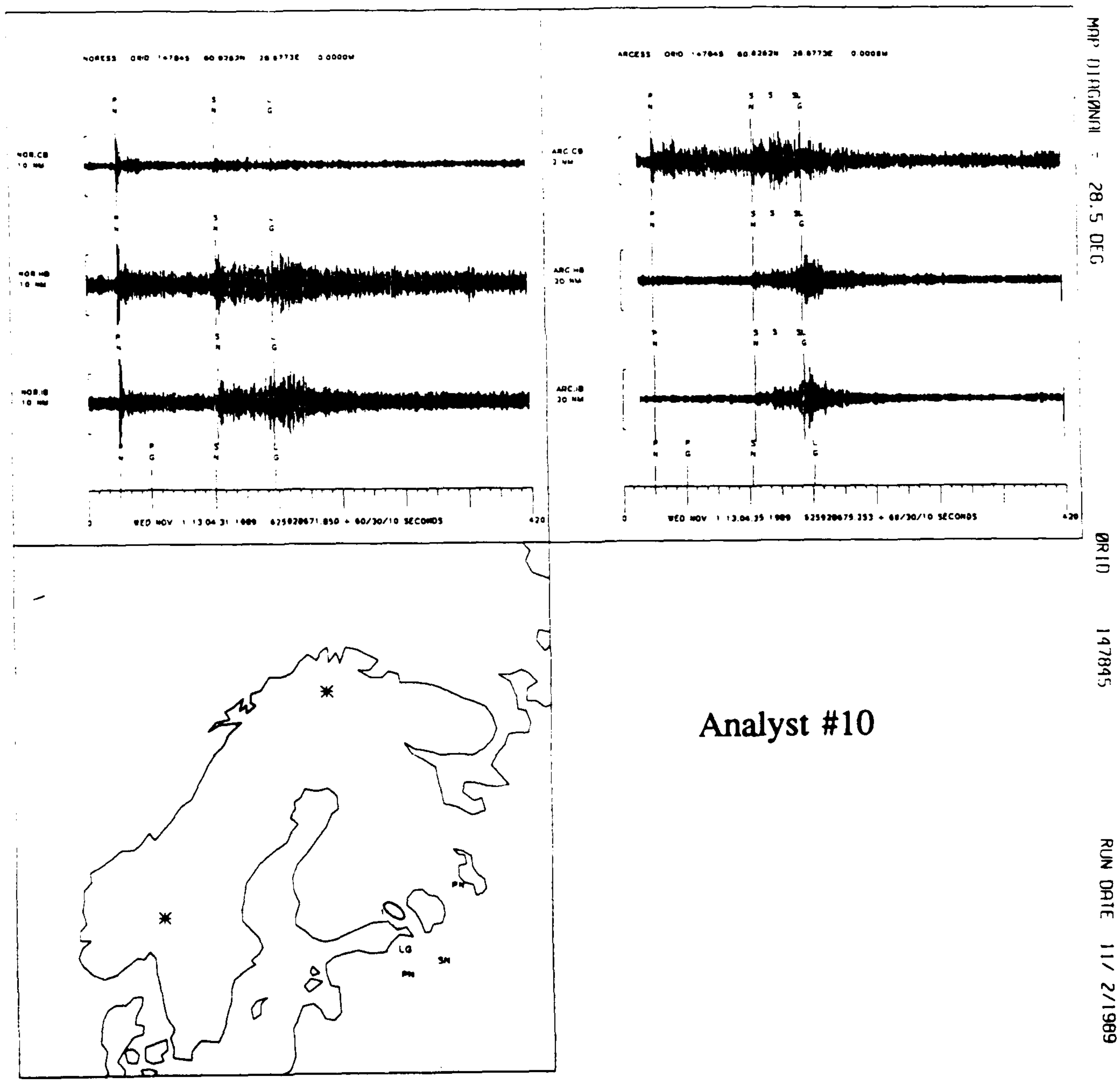
d Nov 1 1989 (N)

	Time	Tad	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
**	13:05:00	1.0	335	11.6	3.7	76.4	7.5	491	4.00	1	0/0	-1
Pn	13:05:01	1.0	335	11.6	3.7	76.4	7.5	491	4.00	1	0/-3	147845
Sn	13:06:34	3.8	221	3.3	0.4	91.9	5.0	429	3.33	3	0/1	147845
Lg	13:07:27	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	147845

Wed Nov 1 1989 (A)

Pn	Time	Tad	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
**	13:05:06	3.9	264	8.0	2.3	169.7	13.0	53	3.16	3	0/0	-1
Pn	13:05:05	3.9	264	8.0	2.3	169.7	13.0	53	3.16	3	0/-1	147845
Sn	13:06:41	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	147845
S	13:06:59	3.9	313	4.5	1.0	170.4	5.1	312	2.22	1	0/0	146579
S	13:07:22	4.0	220	4.0	0.9	159.3	5.5	604	1.82	1	0/-1	146580
Lg	13:07:27	3.6	221	3.4	0.4	160.9	2.7	923	3.16	1	0/-1	147845

Helsinki: 60.7N 29.0E



Analyst #10

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 12:39:17 1989	58.88	9.44	99.9	46.6	28.5

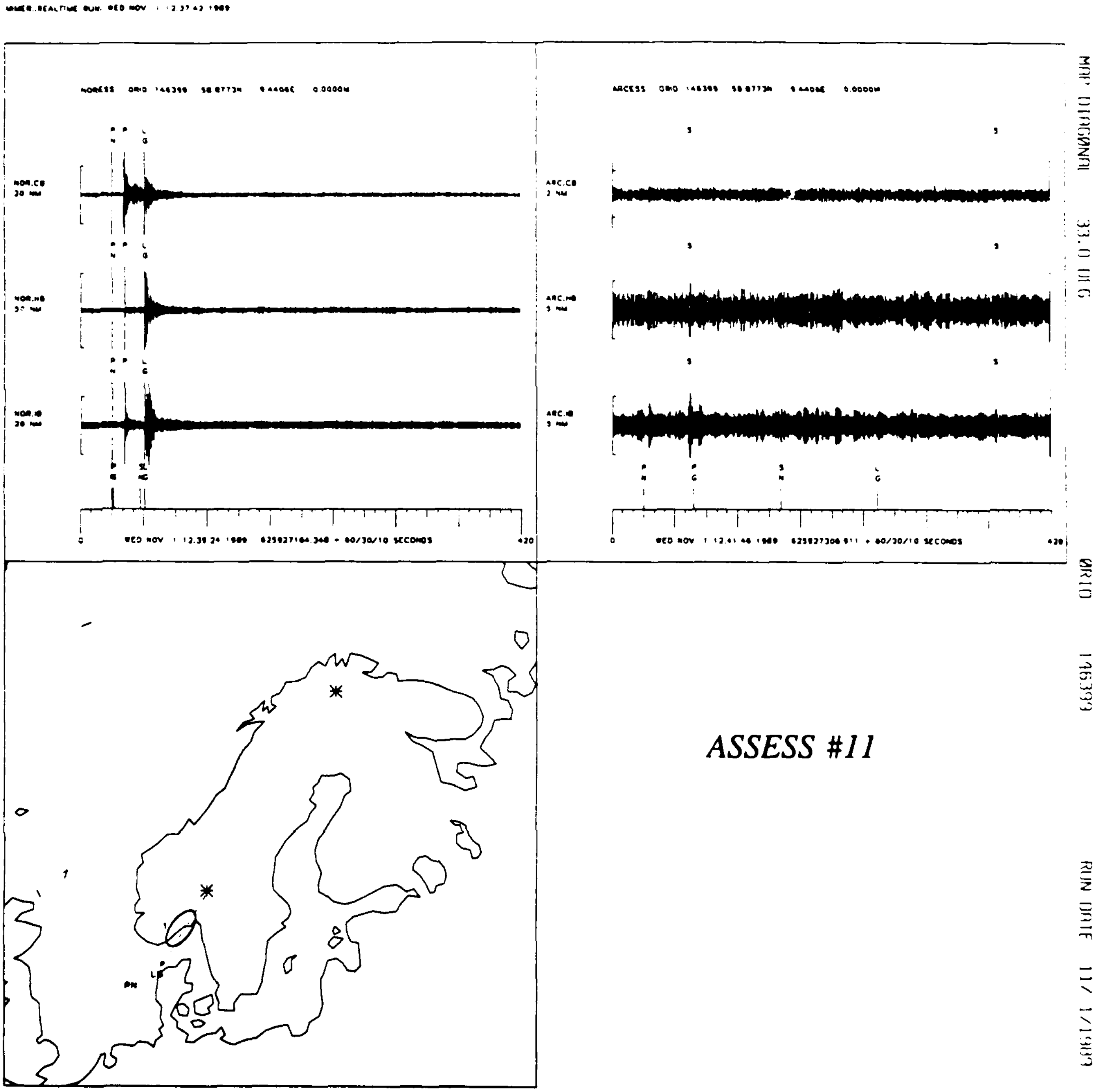
Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89/11/01 12:39 17 667	58 88	9 44	2 14	210 54	93 9	46 6	28 5

Wed Nov 1 1989 (N)

Ph	Time	Tsd	Sen	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12 39 54	3 7	267	6 7	1 2	213 9	4 3	83	4 00	1	0/-3	146399
P	12 40 05	1 0	299	7 3	0 7	206 6	3 2	527	9 57	2	0/-3	146399
Lg	12 40 25	2 0	256	4 0	0 5	206 3	4 5	435	3 33	2	0/-2	146399

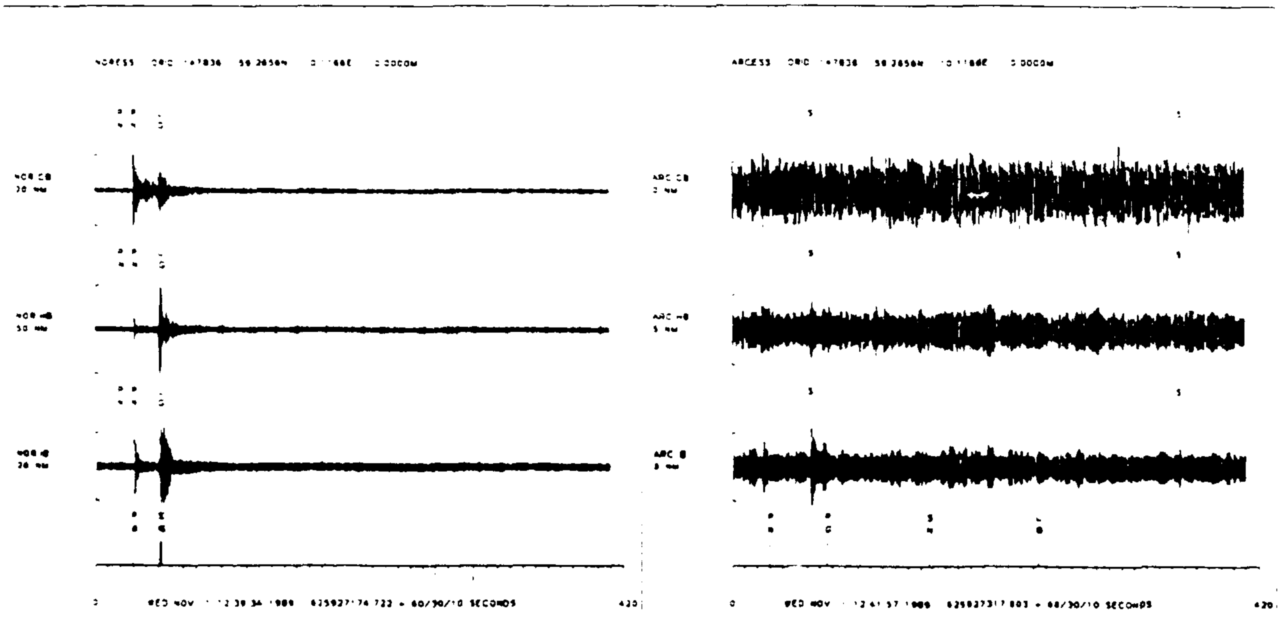
Wed Nov 1 1989 (A)

Ph	Time	Tsd	Sen	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
S	12 43 00	3 8	264	3 0	0 4	179 9	4 0	93	2 86	2	0/0	145313
S	12 47 53	4 0	264	3 0	0 4	179 4	4 0	57	2 95	2	0/-3	145314



ASSESS #11

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 12:39:35 1989	59.27	10.12	69.3	28.8	25.2



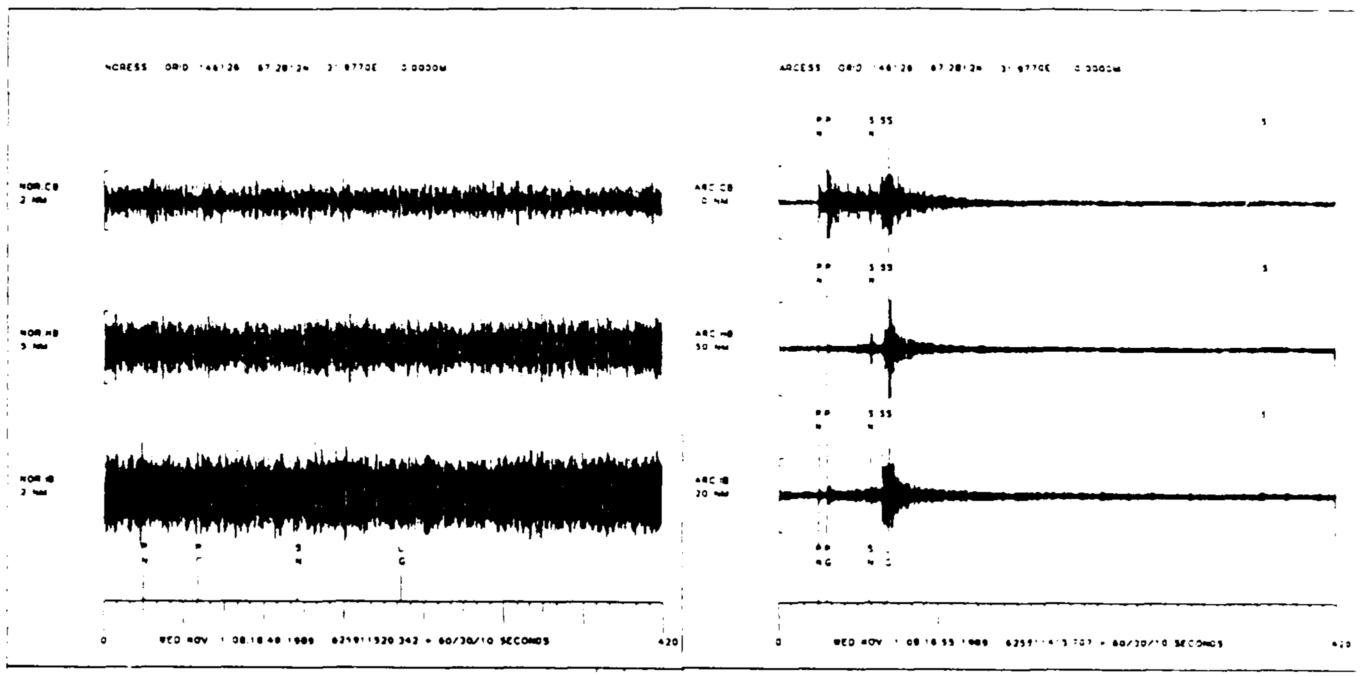
Analyst #11

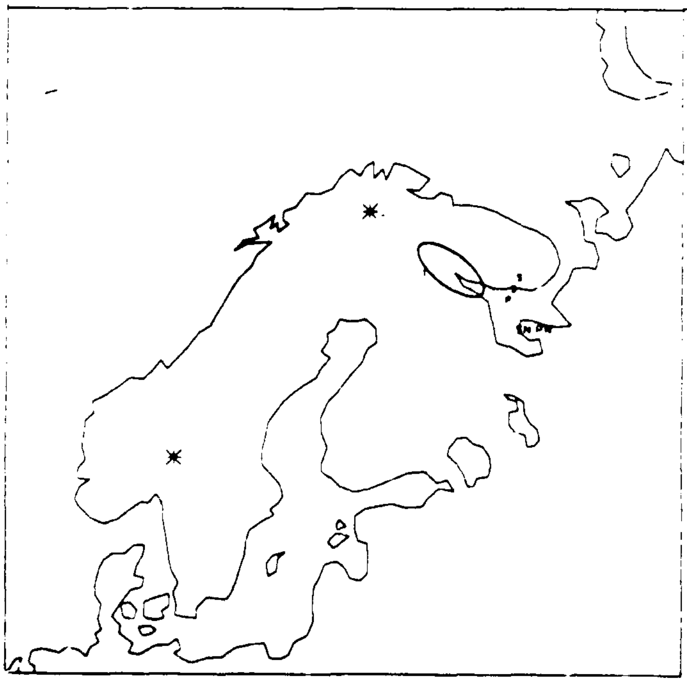
Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	**Wed Nov** 1 08:16:33 1989	67.28	31.98	145.9	58.5	-44.1

\016\020Ph Time Tsd Bmo Vel Dvel Azim Asd Stavg Freq Fsq P/Spl Orid

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fsq	P/Sp.	Orid
Pn	08 17 25	2.0	298	7.2	0.9	127.7	4.1	153	5.57	1	[illegible]	146126
P	08 17 32	2.3	271	7.0	1.5	124.3	5.3	134	3.33	1	[illegible]	146126
Sn	08 18 04	3.3	226	4.2	0.4	131.4	3.4	499	4.52	1	0/0	146126
S	08 18 13	2.3	323	3.5	0.5	117.4	5.0	740	2.61	1	[illegible]	146126
S	08 18 18	2.5	221	4.0	0.5	122.1	3.1	1553	3.33	1	0/0	146126
[illegible]	08 23 00	3.9	310	4.0	.4	17.1	8.5	590	1.22	1	[illegible]	146122





ASSESS #12

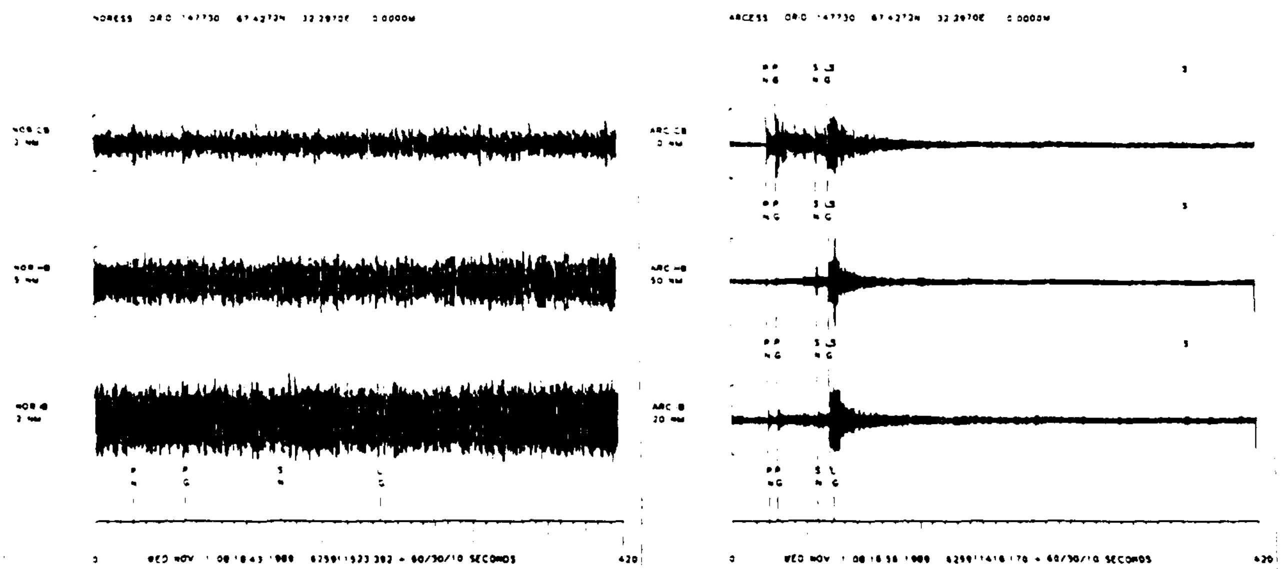
Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 08:16:34 1989	67.43	32.30	55.8	43.4	-46.6

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A):	89/11/01 08:16:33.392	67.28	31.98	3.28	130.38	145.9	58.5	-44.[illegible]

[illegible] Nov [illegible] 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Grid
[illegible]	08:17:25	2.[illegible]	298	[illegible]	[illegible]	127.[illegible]	4.[illegible]	153	6.67	2	0/0	-1
Pn	08:17:25	2.[illegible]	298	[illegible]	[illegible]	127.[illegible]	4.[illegible]	153	6.67	2	-1/-3	147730
[illegible]	08:17:32	2.3	27[illegible]	[illegible]	[illegible]	126.3	5.3	199	3.33	1	0/0	-1
Pg	08:17:33	2.3	27[illegible]	[illegible]	[illegible].6	126.3	5.3	199	3.33	1	-1/-3	147730
[illegible]	08:18:24	3.3	226	4.[illegible]	[illegible].4	131.4	3.4	499	4.62	2	0/0	-1
Sn	08:18:05	3.3	226	4.2	[illegible].4	131.4	3.4	499	4.62	2	0/0	147730
[illegible]	08:18:[illegible]	2.3	313	3.5	[illegible].5	117.4	5.0	760	2.61	2	0/0	1
Lg	08:18:14	2.3	313	3.5	[illegible].5	117.4	5.0	760	2.61	2	0/-1	147730
S	08:18:18	2.5	22[illegible]	4.0	[illegible].5	122.[illegible]	3.[illegible]	1553	3.33	1	0/0	147731
S	08:23:[illegible]	3.3	310	4.0	[illegible].4	[illegible]	8.5	690	[illegible].22	1	[illegible]/-3	146122

[illegible] REALTIME RUN THU NOV 2 [illegible] 1989



Analyst #12

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 11:44:40 1989	66.53	36.38	267.1	90.9	311.1

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A):	89/11/01 11.44 40 799	66 53	36 38	5 05	121 34	257 1	90 9	311 1

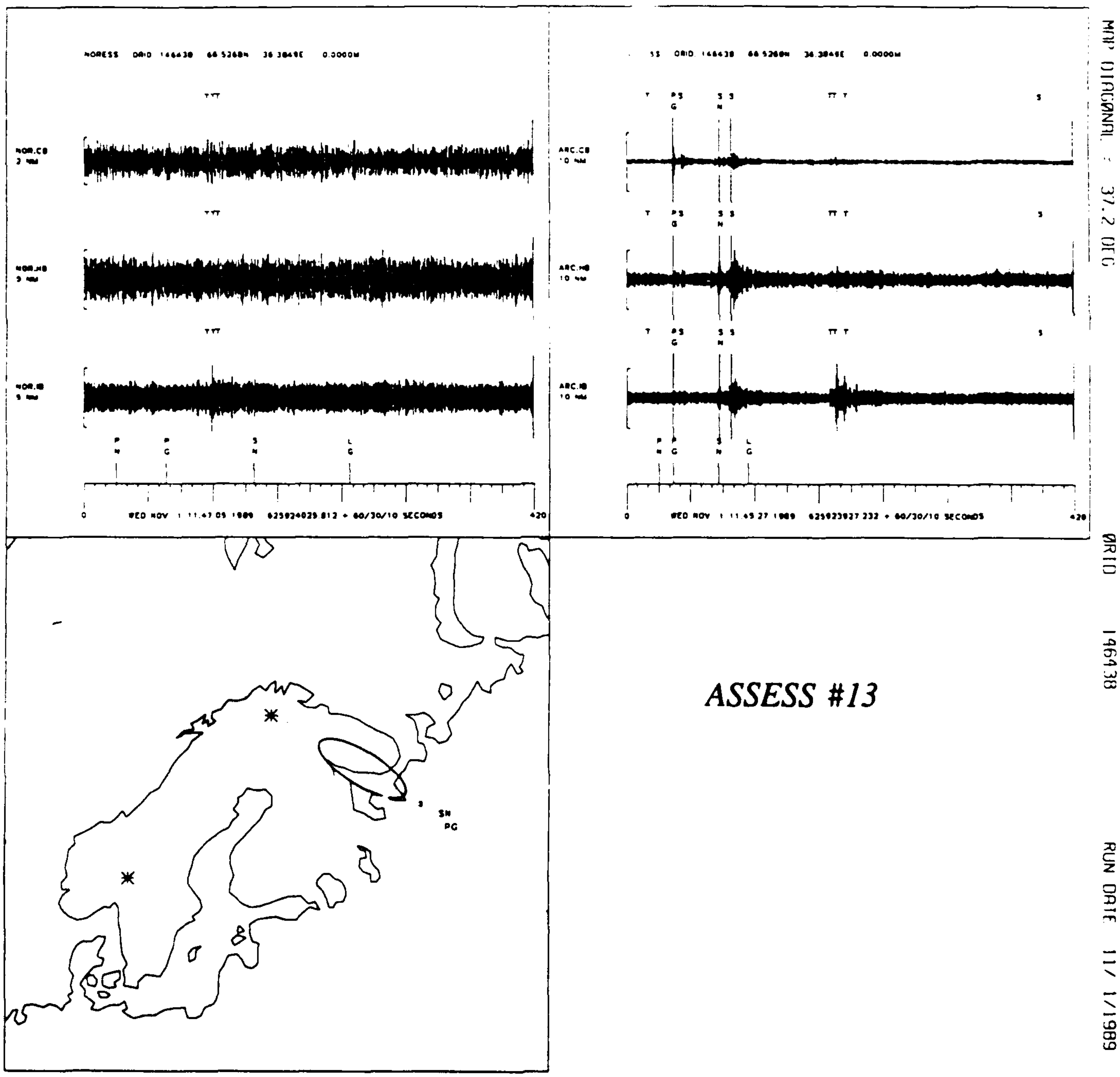
Wed Nov 1 1989 (#)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
T	11 48 59	3 4	202	22 4	24 9	40 6	-40 0	144	2 22	3	0/0	145254
T	11 49 05	2 3	202	38.0	84 7	22 4	-20.0	454	1 87	1	1/-3	145253
T	11 49 09	4 0	310	27 4	51 9	31 9	-20 0	687	1 33	1	1/-3	145252

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
T	11 45.46	3.9	275	55.0	72.0	291 5	40 0	34	4 52	3	0/-3	145245
Pg	11.45:11	1.0	278	7 5	1.3	122.1	3 8	249	5.00	1	-1/-3	145438
S	11:45 17	3.8	310	4 1	1.4	35 8	8 2	792	1 30	1	0/-3	145256
Sn	11.46 54	3 9	225	4 2	0 5	119 9	3 7	204	4 29	2	0/0	145438
S	11.47 05	3.8	256	4 0	0.5	121 3	5 4	81	3 75	3	0/-2	145438
T	11:48:37	2 0	254	81 6	256.2	60.7	-20 0	514	2.86	1	0/1	146250
T	11.48:41	1.8	261	40.6	63.4	83.8	-20 0	500	2.86	1	0/-3	146249
T	11.48.51	3.6	253	140.4	1193.0	54.1	-20 0	499	1 82	1	1/-3	146248
S	11.51:54	4 0	310	5.2	2.3	10 2	15.5	740	1 30	2	1/-3	146257

REALTIME RUN WED NOV 1 12:03:36 1989



ASSESS #13

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 11:45:13 1989	67.48	33.57	54.8	51.3	-51.5

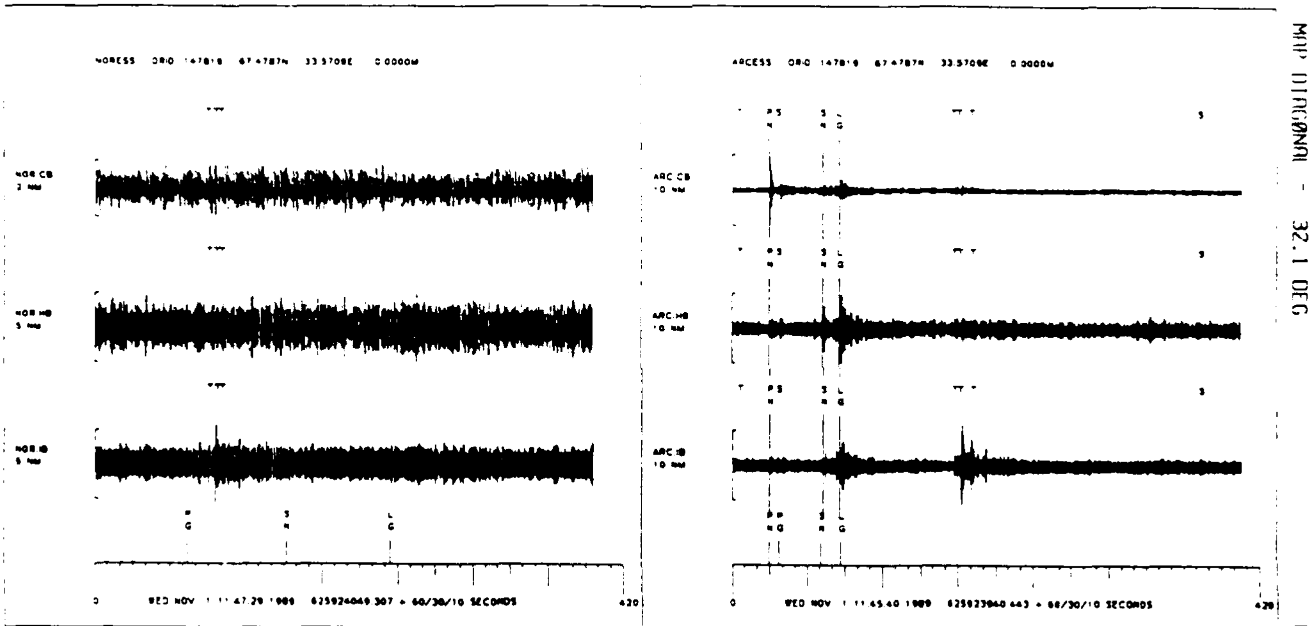
Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A):	89/11/01 11:44:40.799	66.53	36.38	5.05	121.34	267.1	90.9	311.1

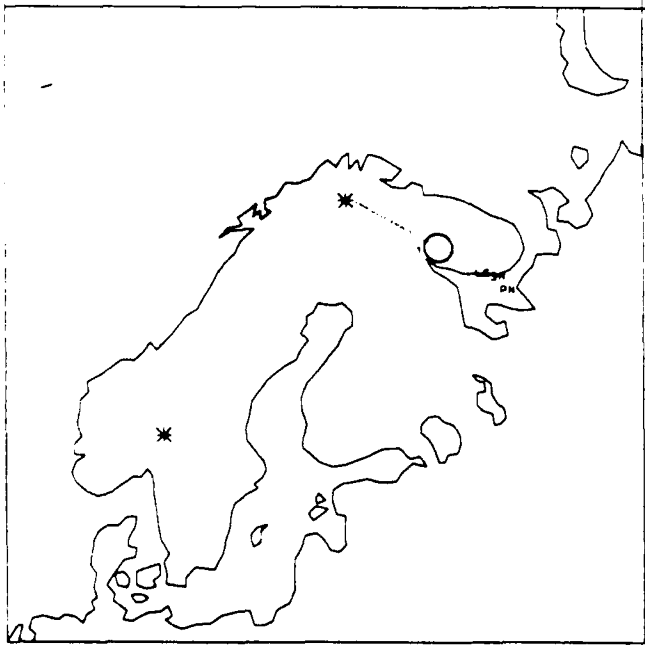
d Nov 1 1989 (N)

Ph	Time	Tsa	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
.	11:48:59	3.4	202	22.4	24.9	40.6	-40.0	144	2.22	3	0/0	146254
T	11:49:05	2.3	202	38.0	84.7	22.4	-20.0	454	1.87	1	1/-3	146253
T	11:49:09	4.0	310	27.4	61.9	31.9	-20.0	687	1.33	1	1/-3	146252
T	11:48:51	3.6	253	140.4	1193.0	54.1	-20.0	499	1.82	1	1/-3	146248
S	11:51:54	4.0	310	5.2	2.3	10.2	15.5	740	1.30	2	1/-3	146257

Wed Nov 1 1989 (A)

Ph	Time	Tsa	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
T	11:45:46	3.9	275	55.0	72.0	291.5	-40.0	34	4.62	3	0/-3	146245
??	11:46:11	1.0	278	7.6	1.3	122.1	3.8	249	10	1	0/0	-1
Pn	11:46:10	1.0	278	7.6	1.3	122.1	3.8	249	10	1	-1/-3	147819
S	11:46:17	3.8	310	4.1	1.4	35.8	8.2	782	1.30	1	0/-3	146256
Sn	11:46:52	3.9	226	4.2	0.5	119.9	3.7	204	4.29	2	0/0	147819
??	11:46:54	3.9	226	4.2	0.5	119.9	3.7	204	4.29	2	0/0	-1
??	11:47:05	3.8	266	4.0	0.5	121.3	5.4	81	3.75	3	0/0	-1
Lg	11:47:06	3.8	266	4.0	0.5	121.3	5.4	81	3.75	3	0/-2	147819
T	11:48:37	2.0	254	81.6	256.2	60.7	-20.0	514	2.96	1	0/1	146250





Analyst #13

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	**Wed Nov 1 12:37:31 1989**	65.93	22.81	146.1	60.8	14.7

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A)	89/11/01 12:37.31 564	65 93	22.91	3 75	197 04	146 1	60 8	14 7

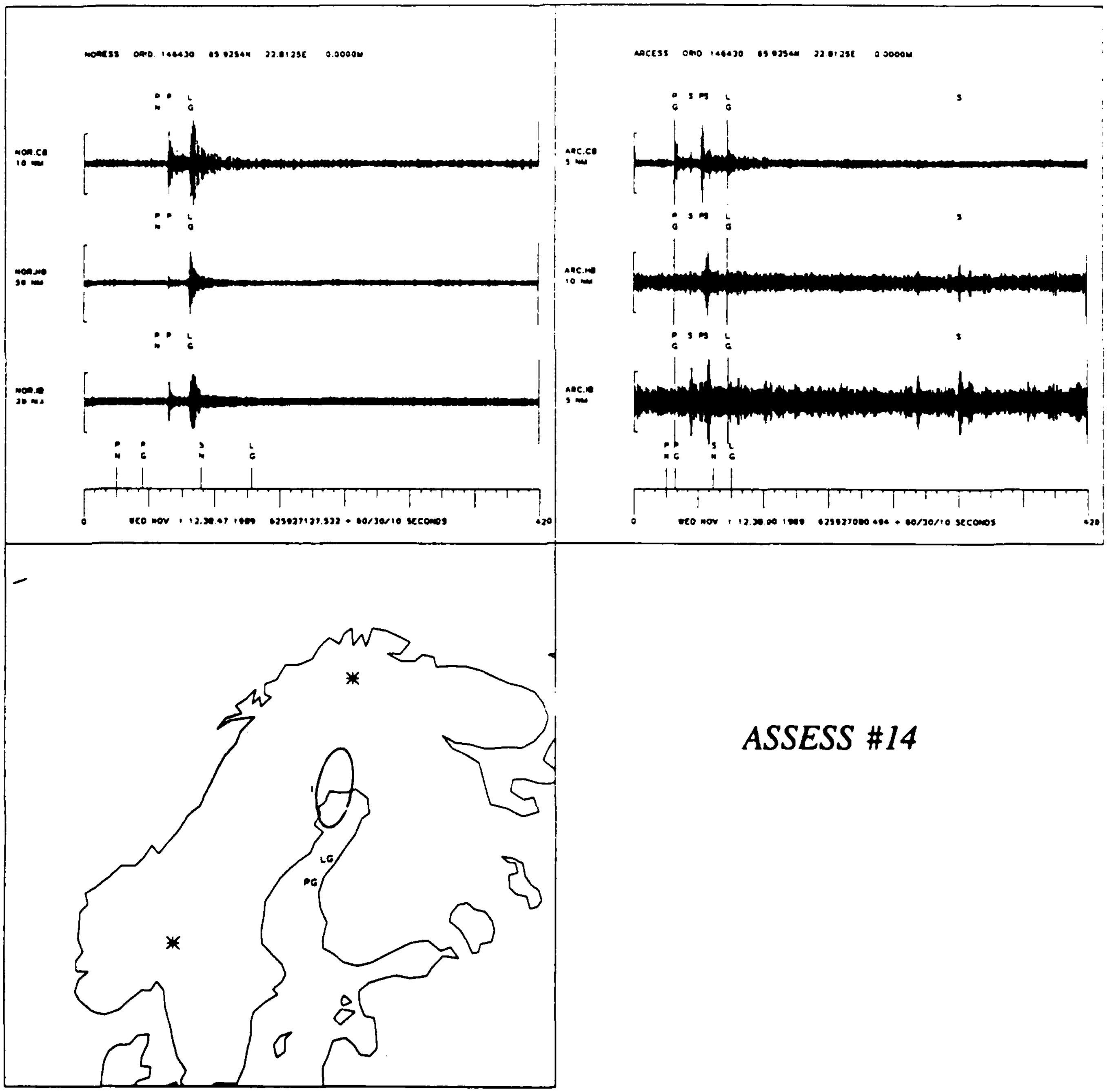
Wed Nov 1 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:39:54	3 7	267	6 7	1 2	213.9	4 3	93	4 00	1	0/-3	146399
P	12 40:05	1 0	299	7 3	0 7	206 6	3.2	527	9.57	2	0/-3	146399
Lg	12.42 25	2 0	256	4 0	0.5	205.3	4 5	405	3 33	2	0/-2	145399

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pg	12:38:38	3 2	285	7.8	1.1	198 7	3 3	79	6 00	1	-1/-2	146430
S	12 38:53	3 9	313	3 0	0 4	179 3	3 2	242	2 40	1	0/-3	146310
P	12:39.03	2 9	286	5 7	0.8	192.8	2 6	158	6.67	1	-1/-2	145311
S	12·39:07	3 1	226	3 7	0 3	197.5	4 3	349	4 29	3	0/0	146312
Lg	12.39:28	3.8	282	4.6	0 4	195 4	3 5	105	6.57	3	0/-2	146430
S	12:43:00	3 8	264	3 0	0.4	179 9	4 0	83	2 86	2	0/0	146313

REALTIME RUN. WED NOV 1 12.29.46 1989



ASSESS #14

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 12:38:01 1989	67.45	23.73	65.3	35.9	16.6

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A).	89/11/01 12:37:31.664	65.93	22.81	3.75	197.34	146.1	60.8	14.7

S 12:43:00 3.8 264 3.0 0.4 179.9 4.0 83 2.06 2 0/0 146313

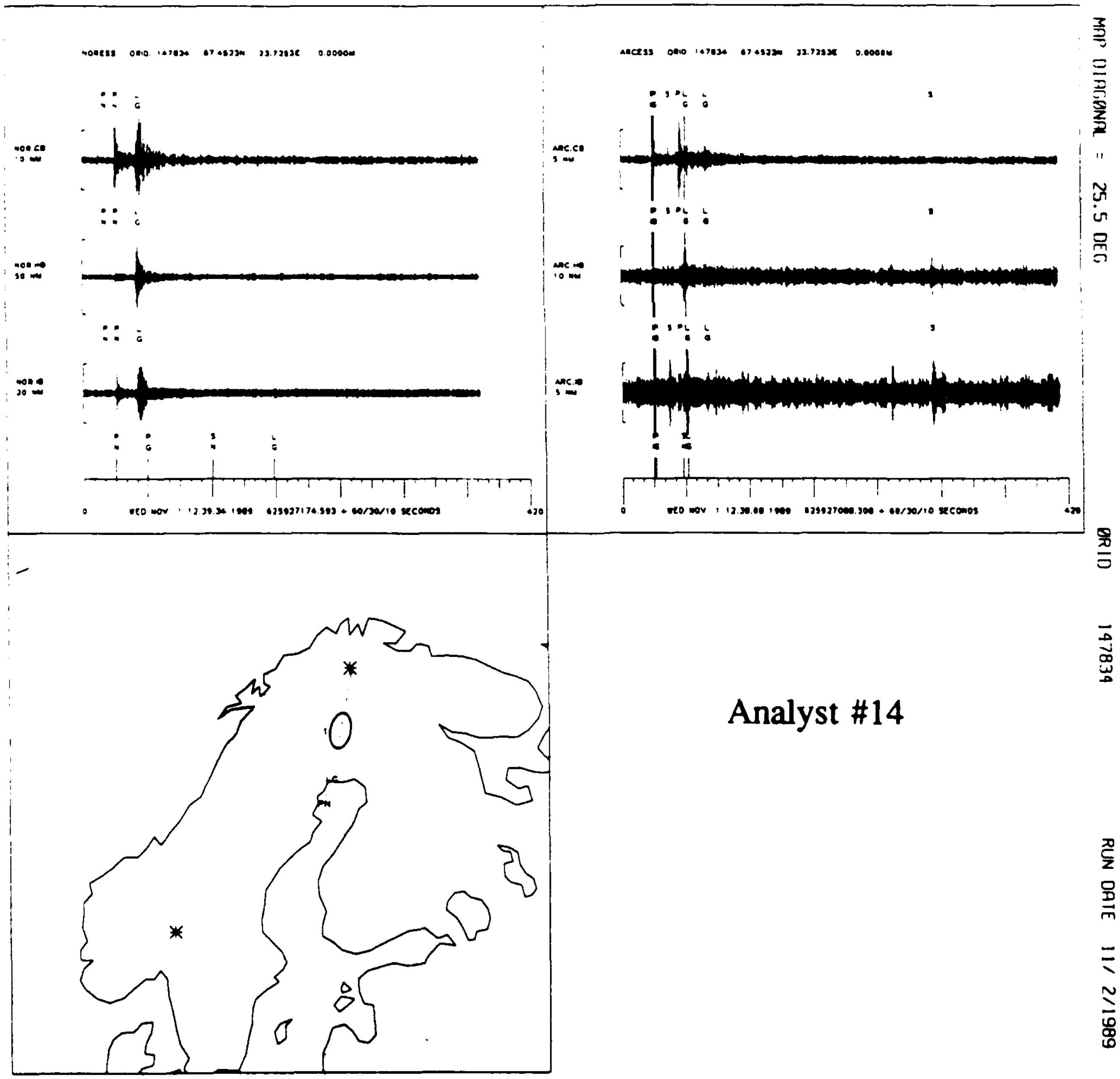
Wed Nov 1 1989 (N)

	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:39:54	3.7	267	6.7	1.2	213.9	4.3	83	4.00	1	0/-3	147837
"	12:40:05	1.0	299	7.3	0.7	206.6	3.2	527	8.57	2	0/0	-1
Pn	12:40:05	1.0	299	7.3	0.7	206.6	3.2	527	8.57	2	0/-3	147836
"	12:40:25	2.0	256	4.0	0.5	206.3	4.5	405	3.33	2	0/0	-1
Lg	12:40:26	2.0	256	4.0	0.5	206.3	4.5	405	3.33	2	0/-2	147836

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
"	12:38:38	3.2	286	7.8	1.1	198.7	3.3	79	6.00	1	0/0	-1
Pn	12:38:38	3.2	286	7.8	1.1	198.7	3.3	79	6.00	1	-1/-2	147834
Pg	12:38:40	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	147834
S	12:38:53	3.9	313	3.0	0.4	179.3	3.2	242	2.40	1	0/-3	146310
P	12:39:03	2.9	206	6.7	0.8	192.8	2.6	168	6.67	1	-1/-2	146311
"	12:39:07	3.1	226	3.7	0.3	197.5	4.3	349	4.29	3	0/0	-1
Lg	12:39:09	3.1	226	3.7	0.3	197.5	4.3	349	4.29	3	0/0	147834

NMRD REALTIME RUN THU NOV 2 17:39:29 1989



Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 23:32:49 1989	67.34	19.94	72.2	41.5	40.9

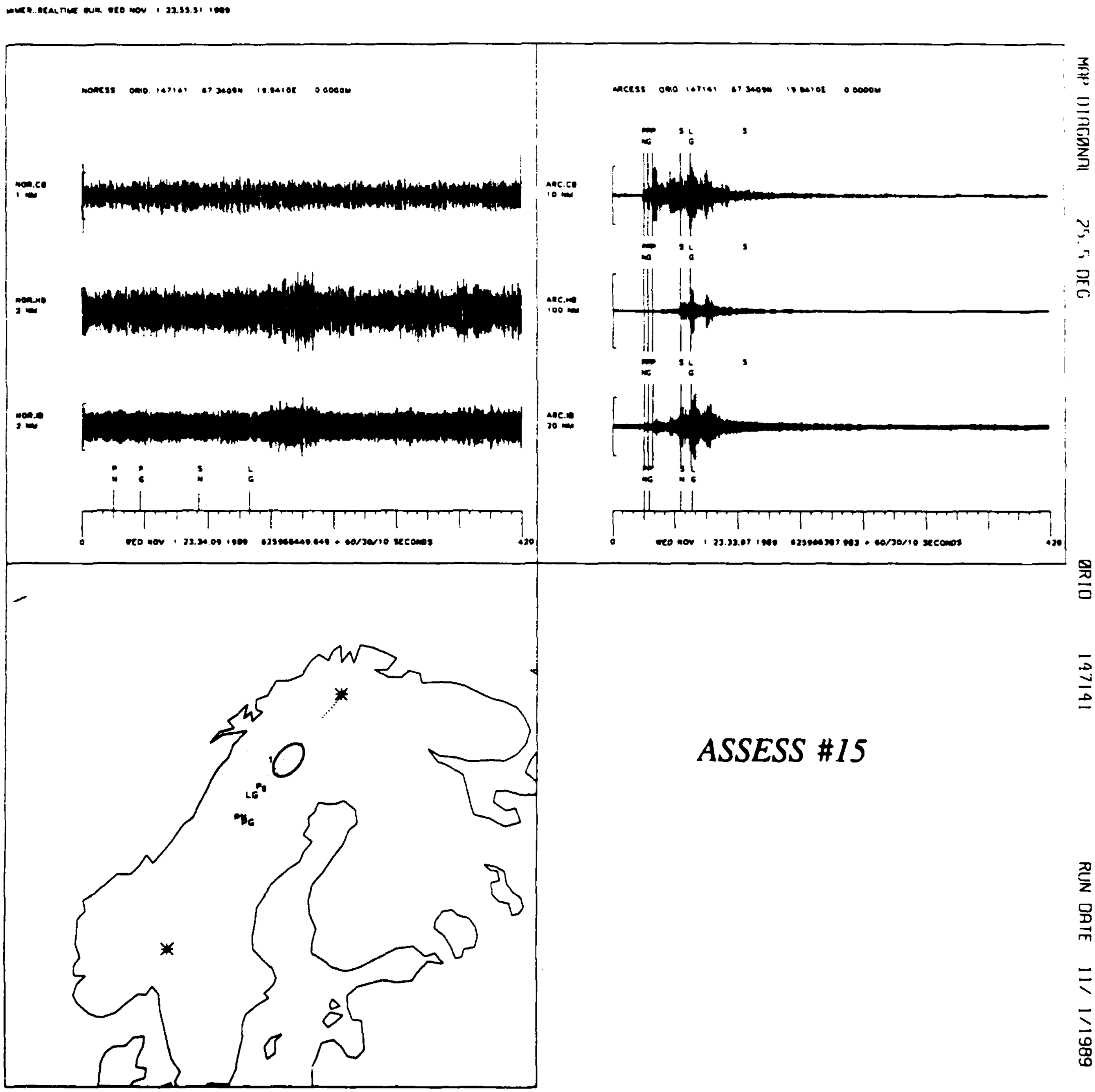
Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A)	89/11/01 23:32:49 490	67 34	19 94	3 00	225 60	72 2	41 5	40 9

Wed Nov 1 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	23.33.37	1 9	279	7 4	1 5	225 8	4 7	94	4 00	1	-1/-1	147141
Pg	23.33:42	3.4	279	7 3	1 4	222.5	4.6	109	4 00	1	-1/-1	147141
P	23:33:46	3 4	286	7.7	1.3	228.3	3.9	243	5 00	1	-1/-1	147141
S	23:34:13	3 3	261	4.7	0.9	225 7	6.3	190	2 86	2	0/0	147141
Lg	23 34.22	3 2	262	4 2	0 6	227 9	3.2	291	3.33	1	1/0	147141
S	23:35:14	4 0	310	4.2	1 8	351 1	14.9	755	1.11	2	1/0	147072



ASSESS #15

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 23:32:56 1989	67.76	20.86	72.0	61.8	41.4

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess A.	89/11/01 23:32:49.490	67.37	19.94	3.00	225.60	72.7	[illegible]	[illegible]

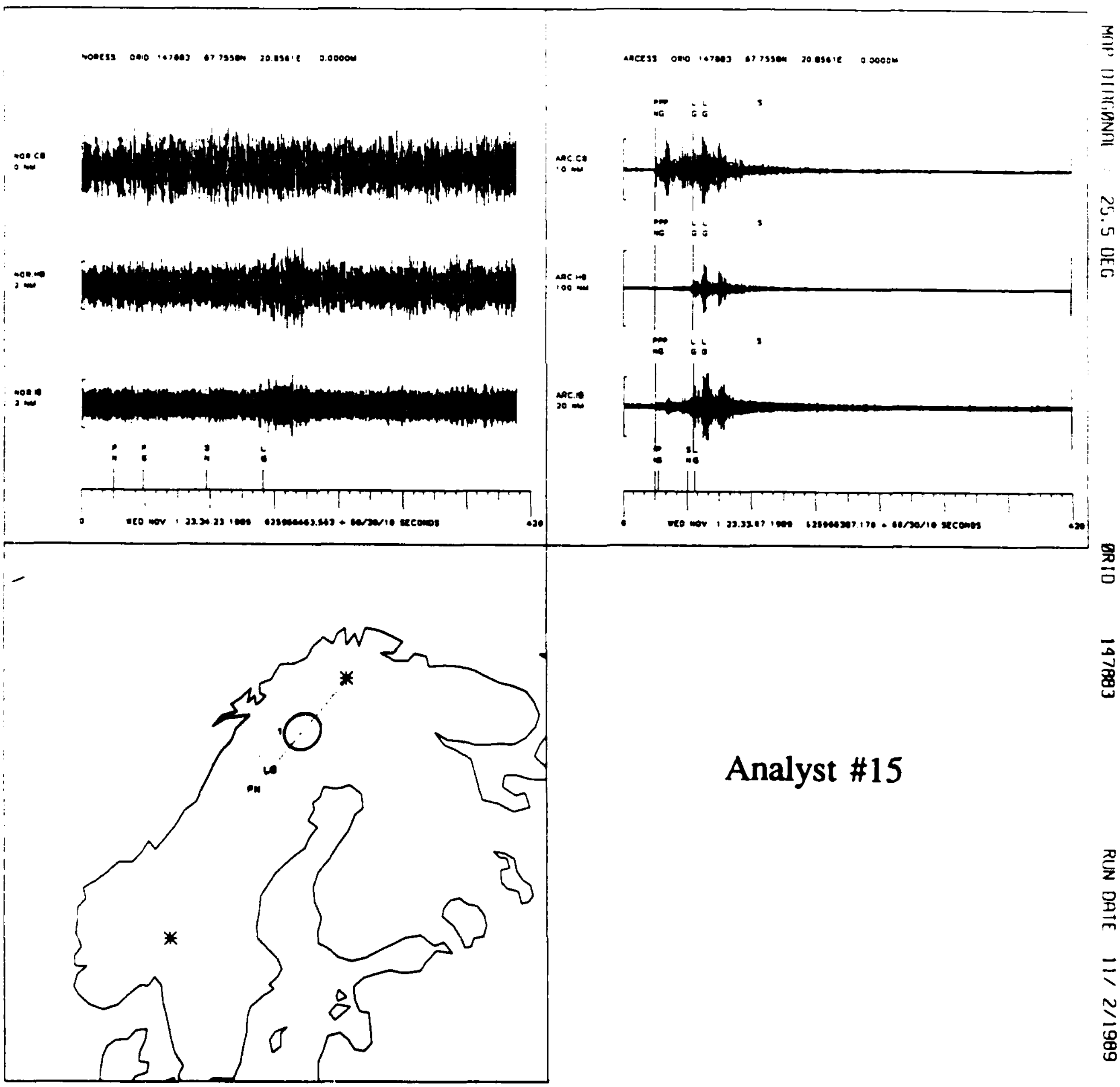
d Nov 1 1989 (N)

Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	F/Spl	Orid

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	F/Spl	Orid
??	23:33:37	1.9	279	7.4	1.5	225.8	4.7	94	4.00	1	0/0	-1
Pn	23:33:37	1.9	279	7.4	1.5	225.8	4.7	94	4.00	1	-1/-1	147883
Pg	23:33:42	3.4	279	7.3	1.4	222.5	4.6	109	4.00	1	-1/-1	147884
P	23:33:46	3.4	286	7.7	1.3	228.3	3.9	243	5.00	1	-1/-1	147885
??	23:34:13	3.3	261	4.7	0.9	225.7	6.3	190	2.86	2	0/0	-1
Lg	23:34:13	3.3	261	4.7	0.9	225.7	6.3	190	2.86	2	0/0	147883
Lg	23:34:22	3.2	262	4.2	0.6	227.9	3.2	291	3.33	1	1/0	147886
S	23:35:14	4.0	310	4.2	1.8	351.1	14.9	755	1.11	2	1/0	147072

NMRES.REALTIME RUN THU NOV 2 18.21 18 1989



Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 07:40:14 1989	62.18	24.64	108.8	41.8	-52.0

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N):	59/12/31 23:59:59.000	-999.00	-999.00	27.32	18.51	-1.0	-1.0	-1.0
Assess(A):	59/12/31 23:59:59.000	-999.00	-999.00	16.99	26.17	-1.0	-1.0	-1.0

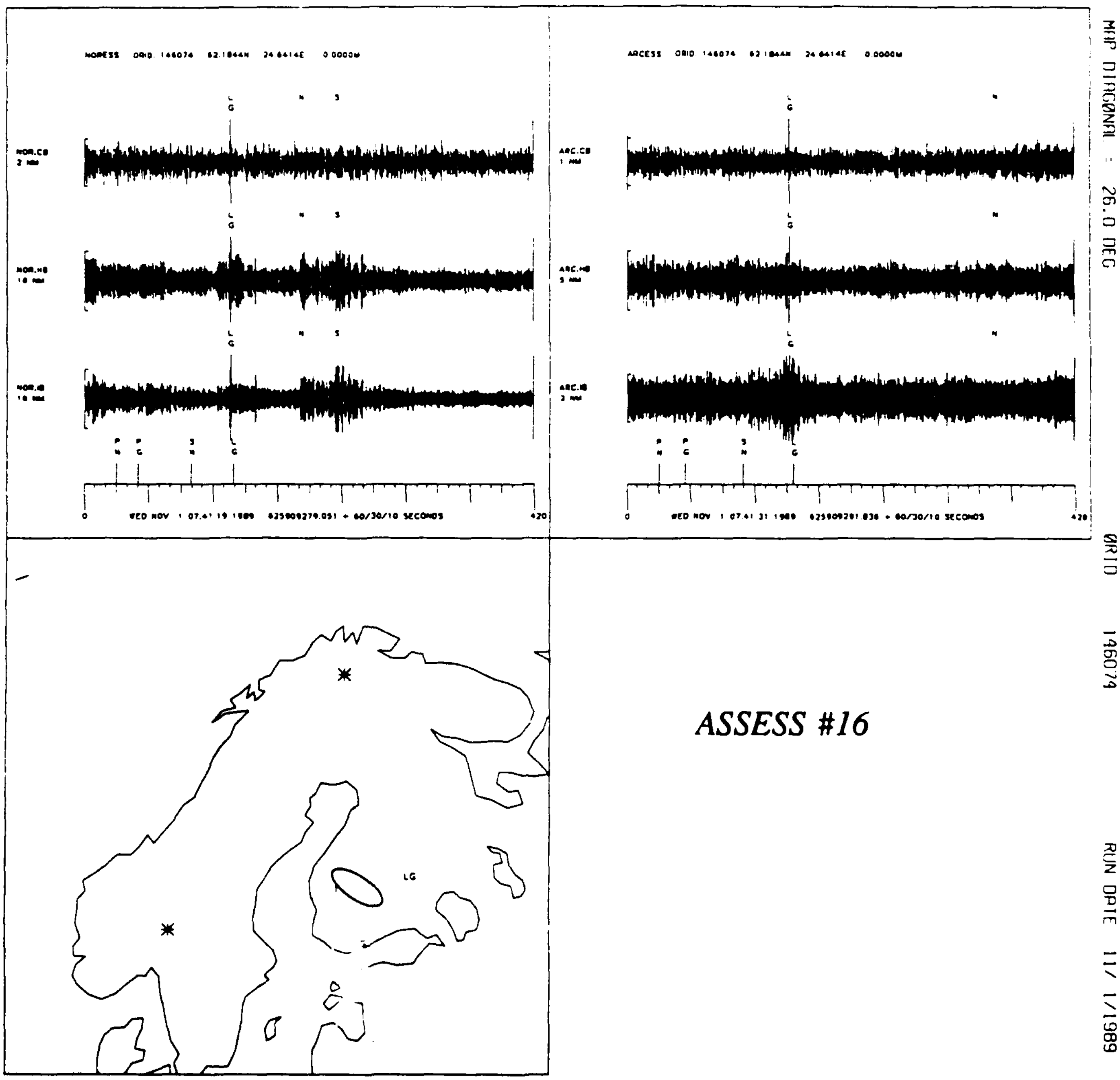
Wed Nov 1 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Lg	07:43:34	3.8	312	2.8	0.3	71.4	2.2	425	3.33	1	0/0	145074
N	07:44:40	3.7	313	2.8	0.3	80.9	2.5	415	2.50	1	0/0	145052
S	07:45:13	4.0	220	2.9	0.4	85.3	3.1	525	2.31	1	0/0	145053

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Lg	07:44:03	3.9	309	3.0	0.3	183.1	3.4	39	3.33	2	0/-1	145074
N	07:47:15	3.7	296	2.5	0.1	201.3	1.3	55	10.00	3	0/-3	145057

NMRD..REALTIME RUN: WED NOV 1 08.03.32 1989



ASSESS #16

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Tue Oct 31 12:44:59 1989	64.64	20.87	116.4	39.4	-51.3

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	69/12/31 23:59:59 000	-999 00	-999 00	27 32	18 61	1 0	1 0	1 0
Assess(A)	69/12/31 23:59:59 000	-999 00	-999 00	16 99	25.17	-1 0	-1 0	-1 0

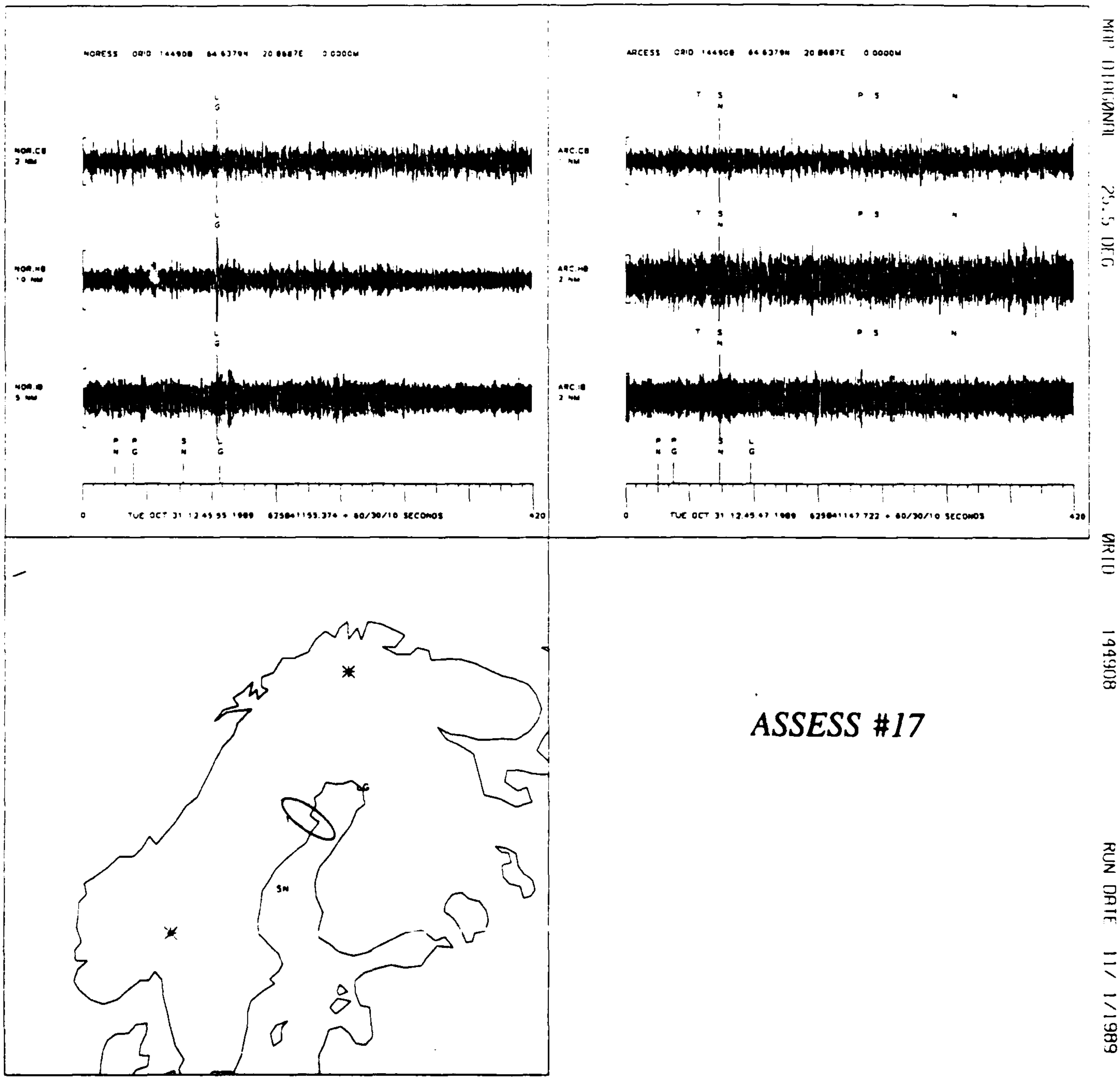
Tue Oct 31 1989 (N)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Grid
Lg	12:47 59	3 7	221	3 1	0 3	45 2	5 1	458	3 00	3	1/2	144908

Tue Oct 31 1989 (A)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Grid
T	12 46.55	3 6	268	38 2	45 5	13 5	-40 0	34	3 53	3	0/-3	144222
Sn	12 47 15	3 9	270	3.0	0 2	203 8	3 9	45	4 00	3	0/-3	144908
P	12 49 27	3 3	275	13.7	5 2	322 2	13 3	42	4 00	2	-1.0	144225
S	12.49:41	3 8	225	3 1	0 3	176 1	3 9	57	4 00	3	1/-1	144229
N	12 50 55	2 5	295	2 3	0 1	241.4	1 2	153	10 00	3	0/-3	144224

REALTIME RUN WED NOV 1 00.57.53 1989



Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 12:28:53 1989	56.19	37.28	256.2	114.0	-6.6

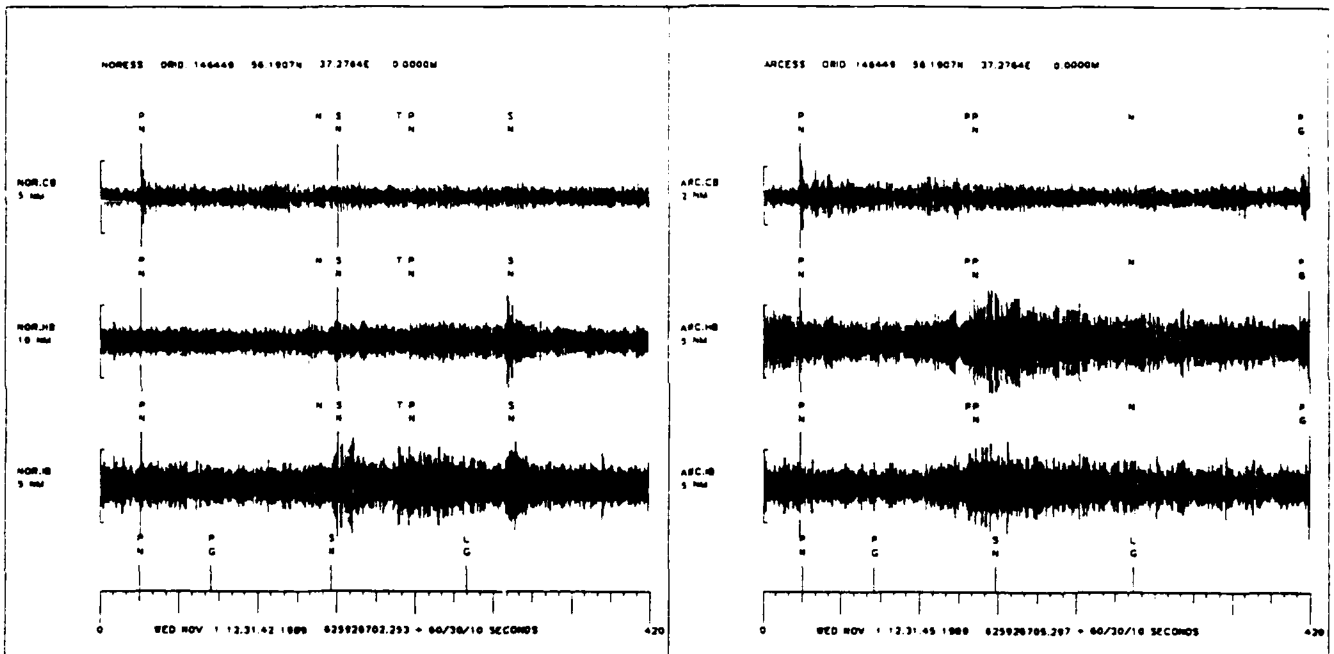
Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N):	89/11/01 12:28:55.505	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Assess(A):	69/12/31 23:59:59.000	-999.00	-999.00	15.99	25.17	-1.0	-1.0	-1.0

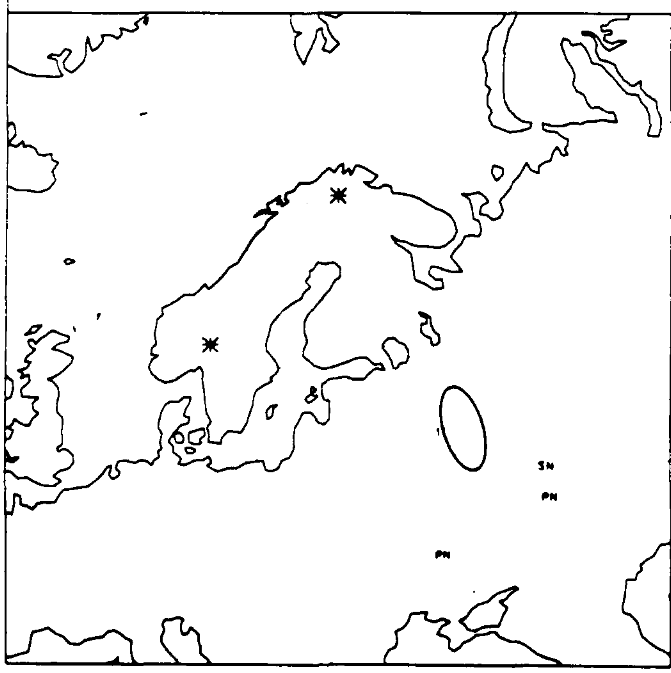
Wed Nov 1 1989 (N)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Amd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:32:13	3.9	249	8.5	3.2	103.2	17.1	127	2.61	3	0/-1	146449
N	12:34:27	3.8	303	2.8	0.3	104.4	6.2	101	2.95	4	0/1	146308
Sn	12:34:42	3.9	260	3.8	0.6	98.7	5.1	127	2.86	2	0/1	146449
T	12:35:29	2.8	254	20.0	17.7	17.2	24.7	186	2.50	1	[illegible]/-3	146305
Pn	12:35:38	3.9	310	9.9	8.0	15.3	21.3	550	1.35	1	1/-3	146446
Sn	12:36:54	3.8	225	4.0	0.4	358.4	[illegible]	271	5.00	2	0/0	146446

Wed Nov 1 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Amd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:32:13	3.9	278	8.7	2.1	164.4	11.1	75	4.00	3	0/-2	146449
P	12:34:21	2.8	201	12.9	14.1	64.8	-30.0	602	1.30	2	0/0	146302
Pn	12:34:27	3.9	248	13.6	11.1	35.2	33.0	345	1.82	2	0/-1	146446
N	12:36:26	2.8	299	2.3	0.1	300.3	1.7	107	8.57	4	0/-3	146300
Pg	12:38:38	3.2	286	7.8	1.1	198.7	3.3	79	5.00	1	-1/-2	146430





MAP DIAGONAL = 50.2 DEG ØRID 146449 RUN DATE 11/ 1/1989

ASSESS #18

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Wed Nov 1 12:30:01 1989	60.62	30.01	104.9	34.2	-34.8

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N):	89/11/01 12:28:55.505	55.87	26.78	14.02	99.03	456.8	207.6	32.7

Wed Nov 1 1989 (N)

Ph	Time	Tsd	Snn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
??	12:32:13	3.9	249	8.6	3.2	103.2	17.1	127	2.61	3	0/0	-1
Pn	12:32:12	3.9	249	8.6	3.2	103.2	17.1	127	2.61	3	0/-1	147831
N	12:34:27	3.8	300	2.8	0.3	134.4	9.2	101	2.86	4	0/1	146308
Lg	12:34:42	3.9	260	3.8	1.6	98.7	5.1	127	2.86	2	0/1	147831
T	12:35:28	2.8	254	20.0	17.7	17.2	24.7	188	2.50	1	1/-3	146305
P	12:35:38	3.9	310	9.9	8.0	15.3	21.3	650	1.36	1	1/-3	147832
S	12:36.54	3.8	225	4.0	0.4	358.4	3.1	271	5.00	2	0/0	147832

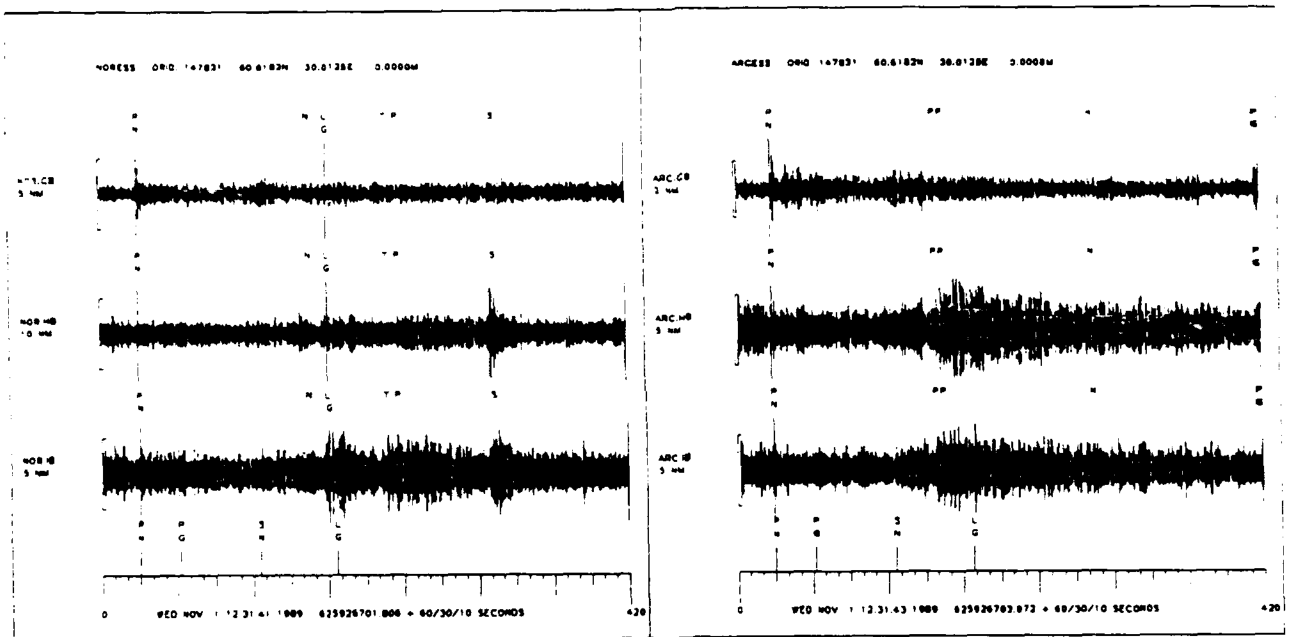
Pn	12:30:38	3.2	286	7.8	1.1	190.7	3.3	79	6.00	1	-1/-2	147834
Pg	12:30:40	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0.0	147834

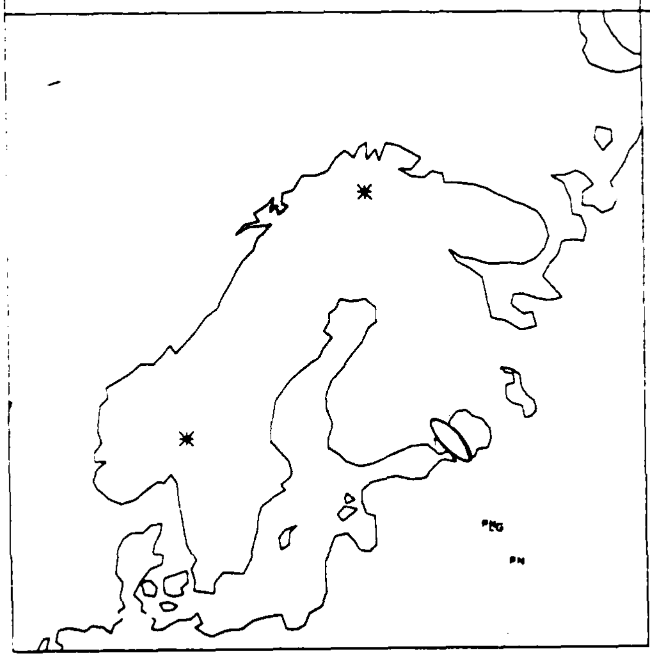
Wed Nov 1 1989 (A)

Ph	Time	Tsd	Snn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	12:32:12	3.9	278	8.7	2.1	164.4	11.1	75	4.00	3	0/-2	147831
??	12:32:13	3.9	278	8.7	2.1	164.4	11.1	75	4.00	3	0/0	-1
P	12:34:21	2.8	201	12.9	14.1	64.8	-30.0	602	1.30	2	0/0	146302
P	12:34:27	3.9	248	13.6	11.1	35.2	33.0	345	1.82	2	0/-1	147832
N	12:36:26	2.8	299	2.3	0.1	300.3	1.7	107	8.57	4	0/-3	146300

NMRER REALTIME RUN THU NOV 2 17:37:40 1989

Helsinki: 60.994N 29.381E





Analyst #18

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Thu Nov 2 09:42:38 1989	59.98	22.00	102.2	48.0	-42.5

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	69/12/31 23:59:59.000	-999.00	-999.00	27.32	18.61	-1.0	-1.0	-1.0
Assess(A)	89/11/02 09.42.21.950	59.11	22.55	10.50	188.09	333.0	170.9	5.5

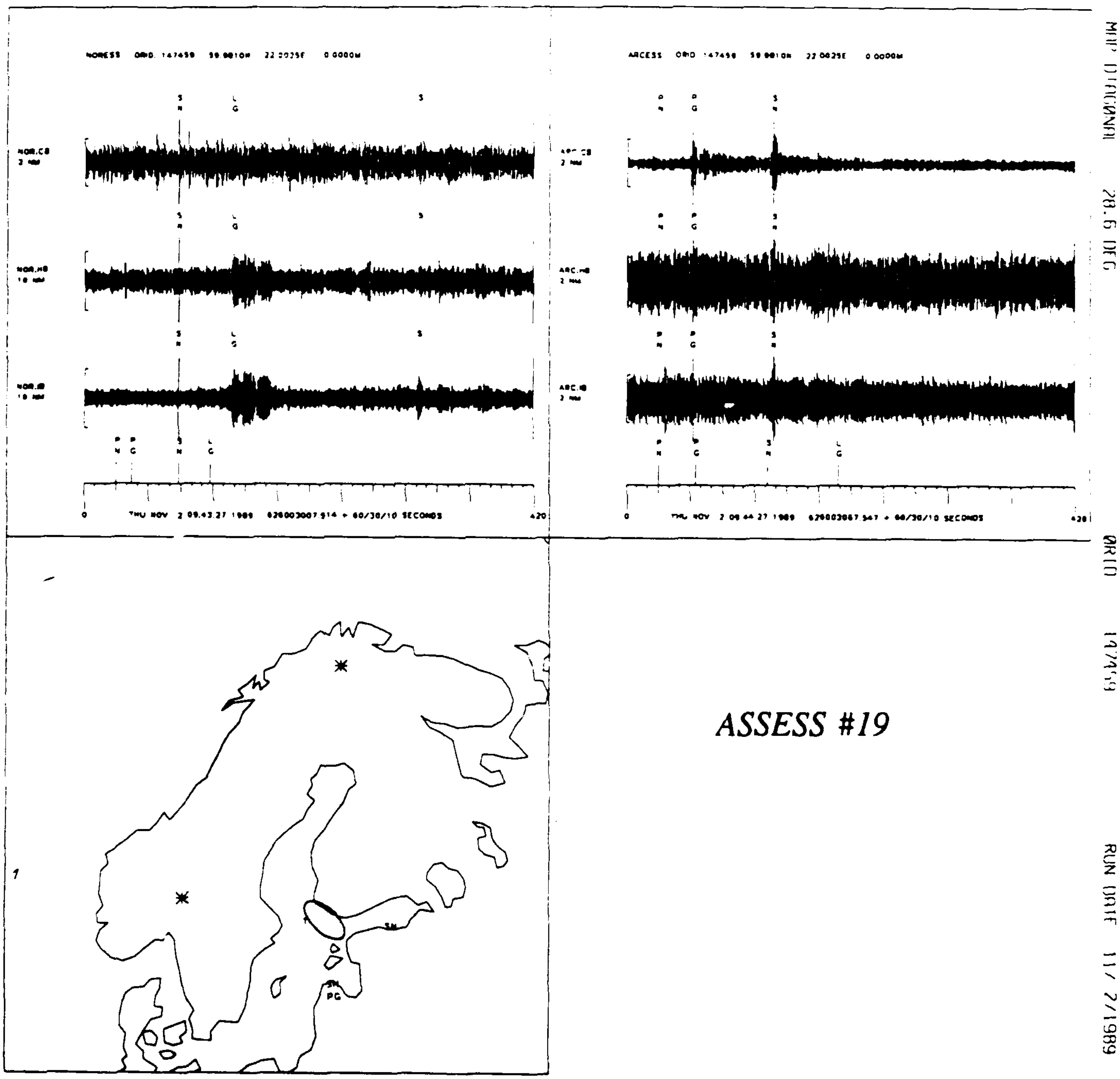
Thu Nov 2 1989 (N)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Sn	09 44 54	4.0	228	3.5	0.2	92.3	2.3	215	7.50	3	0/1	147459
Lg	09 45 45	3.2	313	2.9	0.4	45.4	3.1	577	2.31	1	1/-3	147451
S	09 48 40	3.9	313	2.9	0.4	67.7	2.9	435	2.50	1	1/-3	147430

Thu Nov 2 1989 (A)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	09 44:58	4.0	303	6.1	1.8	82.2	14.0	57	2.22	3	1/-1	147461
Pg	09 45:29	3.7	279	7.7	1.6	187.9	9.7	45	4.00	3	0/-1	147459
Sn	09 46 44	3.4	225	4.6	0.5	188.1	2.5	148	4.52	1	0/-2	147459

NMER REALTIME RUN THU NOV 2 07 21.13 1989



Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Thu Nov 2 09:43:46 1989	62.67	23.39	106.7	58.2	-83.8

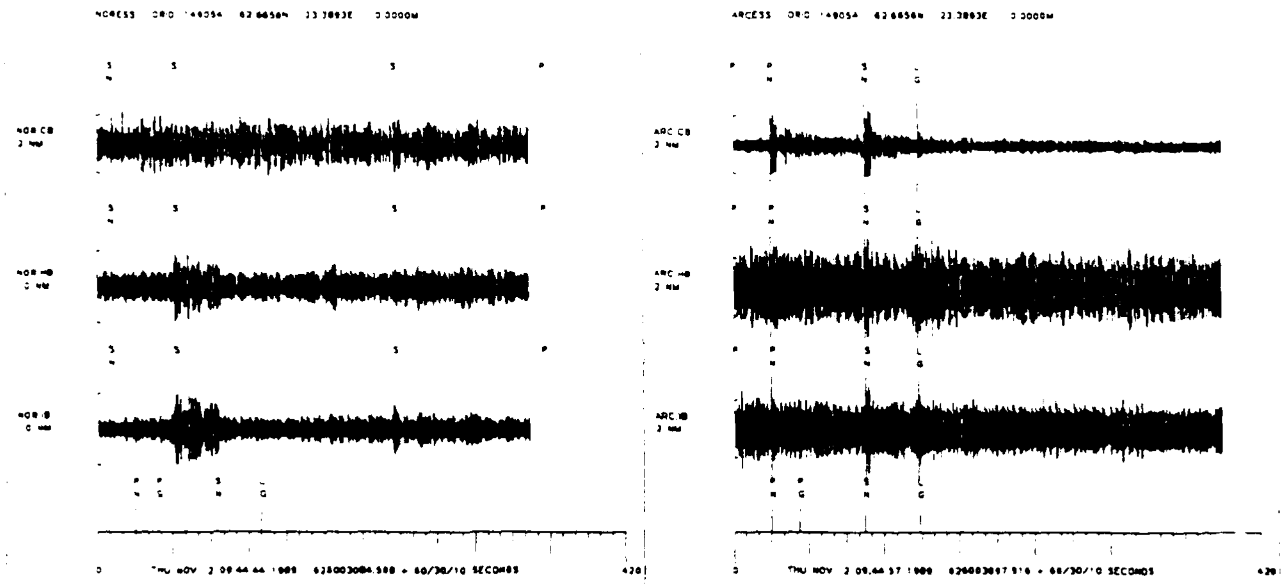
Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A)	89/11/02 09:42:21.950	59.[illegible]	22.65	[illegible]	108.08	333.0	170.9	5.5

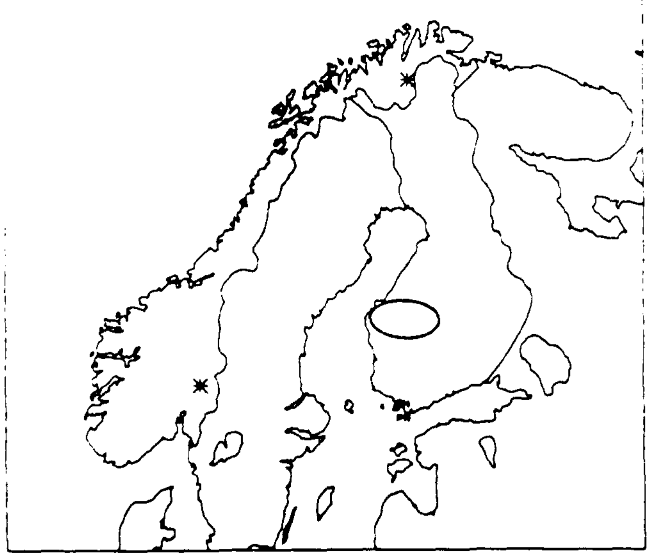
[illegible] Nov 2 1989 (N)

Ph	Time	Tsd	Smn	Vel	Dvel	Azim	Aed	Stavg	Freq	Fkq	P/Spl	Orid
Sn	09:44:54	4.0	228	3.5	0.2	92.3	2.3	216	7.50	0	0/1	149055
S	09:45:46	3.2	313	2.8	0.4	85.4	[illegible]	577	2.31	1	1/-0	149100
S	09:48:40	3.8	313	2.9	0.4	67.7	2.9	436	2.50	1	1/-3	147400
P	09:53:38	3.9	279	7.5	1.2	199.3	7.6	91	5.00	0	0/2	147429

Thu Nov 2 1989 (A)

Ph	Time	Tsd	Smn	Vel	Dvel	Azim	Aed	Stavg	Freq	Fkq	P/Spl	Orid
P	09:44:58	4.0	303	6.1	1.8	82.2	14.0	57	2.22	3	-1/-1	149100
Pn	09:45:27	3.7	279	7.7	1.6	187.9	9.7	45	4.00	0	0/-1	149054
??	09:45:29	3.7	279	7.7	1.6	187.9	9.7	45	4.00	3	0/0	-1
Sn	09:46:43	3.4	225	4.6	0.5	188.1	2.5	148	4.62	1	0/-2	149054
??	09:46:44	3.4	225	4.4	0.5	188.1	2.5	148	4.62	1	0/0	-1
Lg	09:47:35	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	149054





Analyst #19

25.5 DEG

ORID 149054

RUN DATE 11/ 5/1989

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Fri Nov 3 08:19:37 1989	67.8[illegible]	33.95	40.0	29.3	65.3

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N):	89/11/03 08:19:37.875	68.09	34.41	12.19	43.37	402.1	96.8	-25.9
Assess(A):	89/11/03 08:19:37.336	67.65	33.60	3.50	118.70	80.9	42.2	35.7

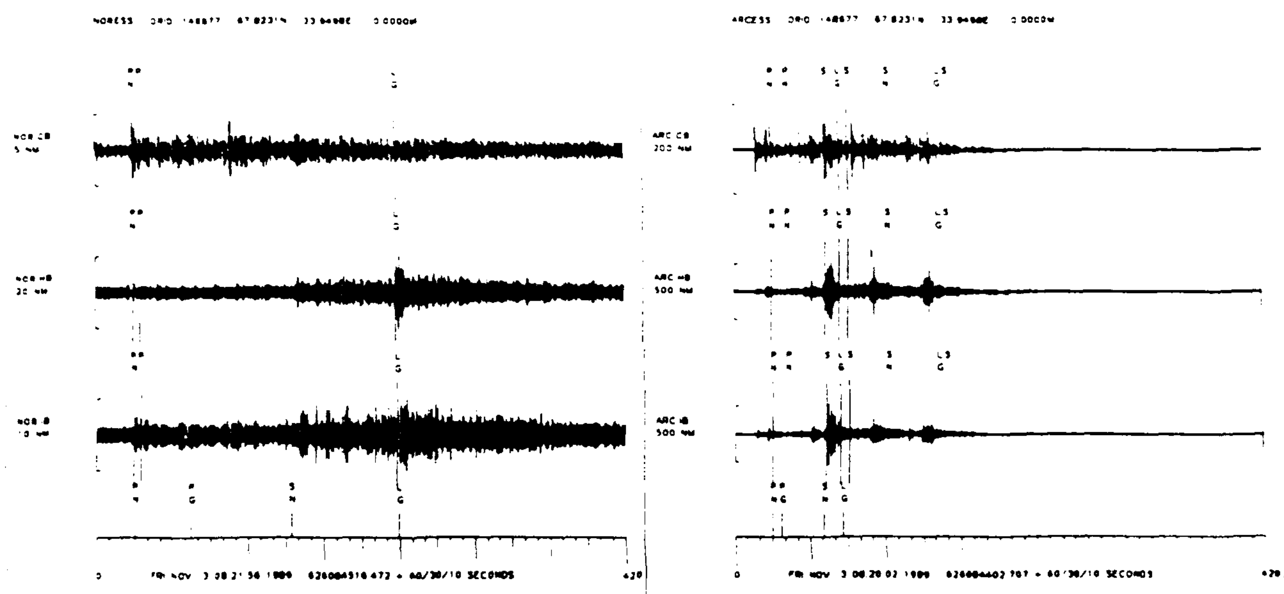
[illegible] Nov 3 1989 (N)

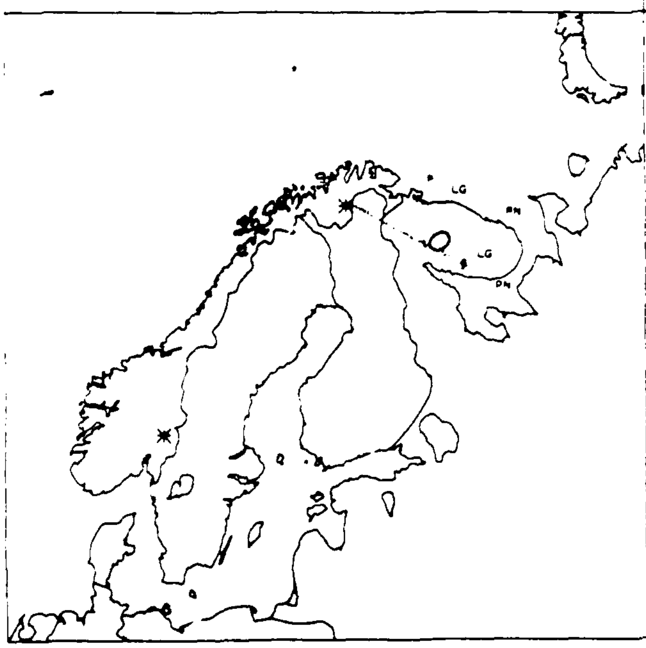
Ph	Time	Tsd	Smn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	08:22:25	2.0	328	8.5	2.4	46.7	6.5	185	3.33	1	0/0	140677
P	08:22:31	3.6	329	9.9	3.0	35.2	10.7	151	3.53	2	0/0	140677
Lg	08:25:54	3.9	312	3.7	1.2	39.4	7.3	858	1.33	[illegible]	[illegible]/-3	140677

Fri Nov 3 1989 (A)

Ph	Time	Tsd	Smn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	08:20:32	1.0	278	7.8	1.4	120.4	4.0	2809	5.00	1	0/-3	140677
Pn	08:20:45	3.8	267	7.4	1.8	108.8	11.3	895	3.33	3	0/-2	140657
S	08:21:15	3.6	253	4.2	0.6	121.3	3.2	1610	3.33	1	0/-1	140677
Lg	08:21:26	1.6	313	3.1	0.4	112.7	6.2	18997	2.50	3	0/-1	140677
S	08:21:33	4.0	309	4.8	0.7	119.9	5.4	2603	3.33	2	0/-2	140677
Sn	08:22:04	3.5	220	3.7	0.7	119.9	4.4	8861	2.14	1	0/0	140657
Lg	08:22:45	3.7	303	3.2	0.3	117.1	3.4	2388	3.53	2	0/0	140657
S	08:22:50	3.9	226	5.4	0.7	120.3	6.4	11944	4.29	3	0/0	140657

[illegible] REALTIME RUN FRI NOV 3 [illegible] 1989





ASSESS #20

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Asses:	Fri Nov 3 08:19:34 1989	67.68	34.32	35.9	18.9	-82.3

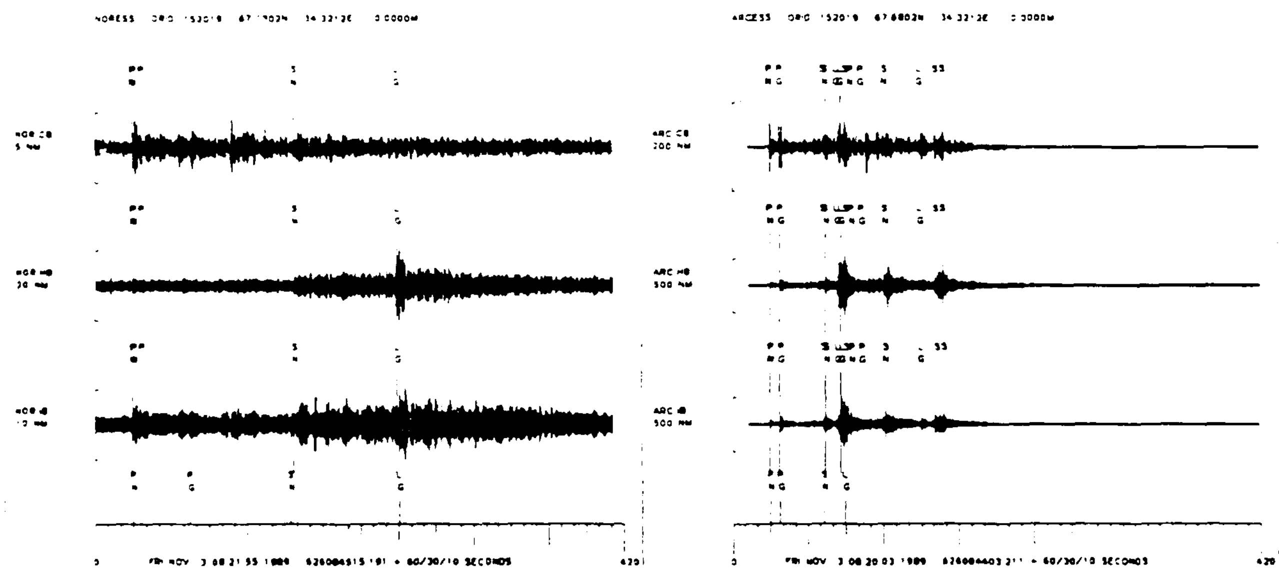
Fri Nov 3 1989 (N)

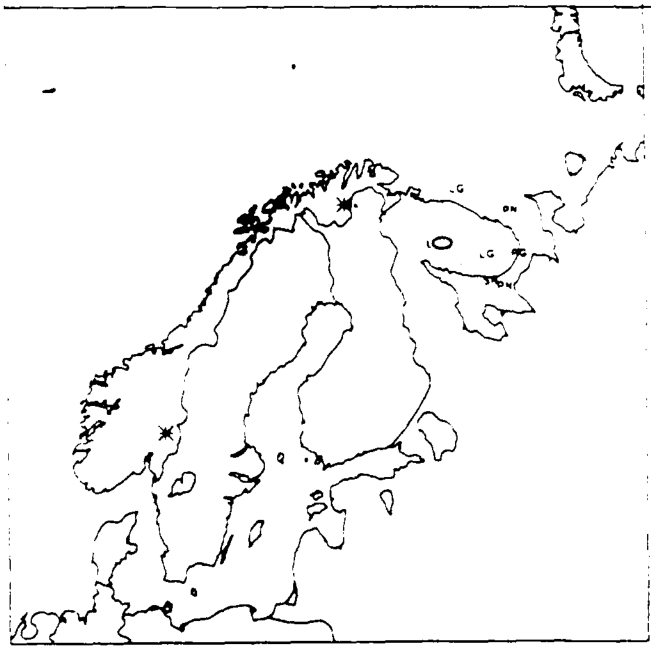
Ph	Time	Tsd	Smn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	08:22:25	2.0	308	8.5	2.4	46.7	6.5	.85	3.33	1	0/0	152027
	08:22:24	2.0	308	8.5	2.4	46.7	6.5	.85	3.33	1	0/0	152019
	08:22:31	3.6	309	9.9	3.0	35.2	[illegible]	.51	3.53	2	0/0	152028
Sn	08:24:02	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	152019
Lg	08:25:54	3.9	3.0	[illegible]	[illegible]	29.4	7.3	854	1.00	1	[illegible]	152019

Fri Nov 3 1989 A

Ph	Time	Tsd	Smn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	08:22:32	1.0	278	7.8	1.4	120.4	4.0	2809	5.00	1	0/-3	152024
Pn	08:22:33	1.0	278	7.8	1.4	120.4	4.0	2809	5.00	1	0/-3	152019
Pg	08:22:41	3.8	267	7.4	1.8	108.8	11.0	895	3.33	3	0/-2	152019
[illegible]	08:22:45	3.8	267	7.4	1.8	108.8	11.0	895	3.33	3	0/0	[illegible]
S	[illegible]	3.6	253	4.2	[illegible]	[illegible]	3.2	1610	3.33	1	0/-1	152025
Sn	[illegible]	3.6	253	4.2	0.6	121.3	3.2	1610	3.33	1	0/-1	152019
Lg	[illegible]	1.6	303	3.1	0.4	[illegible]	6.2	10997	2.50	3	0/-1	152026
Lg	[illegible]	1.6	303	3.1	0.4	[illegible]	6.2	10997	2.50	3	0/-1	152019
S	[illegible]	4.0	309	4.8	0.7	[illegible]	5.4	[illegible]	[illegible]	2	0/-2	152023
Pn	[illegible]	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	152023

Sn	08:22:04	3.5	220	3.7	0.7	119.9	4.4	8861	2.14	1	0/0	152020
Lg	08:22:32	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	152023
S	08:22:45	3.7	303	3.2	0.3	117.1	3.4	2388	7.53	2	0/0	152023
S	08:22:50	3.9	226	5.4	0.7	128.0	6.4	11944	4.29	3	0/0	152022





MAP ORIGIN 32.6 DEG ORID 152019 RUN DATE 11/ 6/1989

Analyst #20

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Fri Nov 3 08:19:00 1989	65.37	40.92	114.0	103.7	41.9

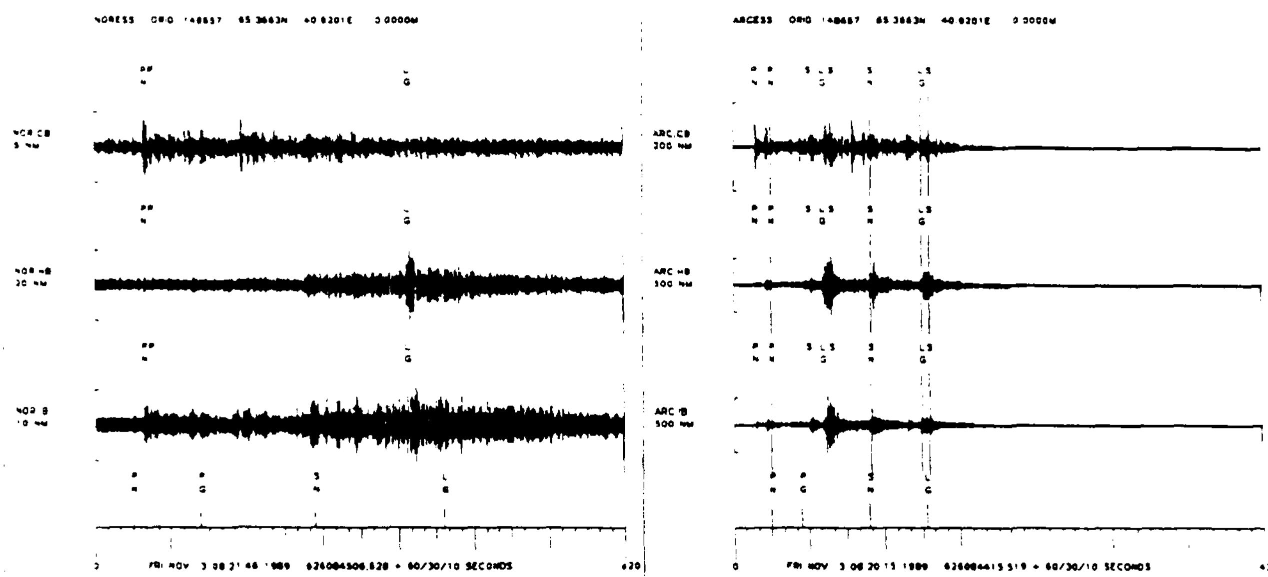
Fri Nov 3 1989 (N)

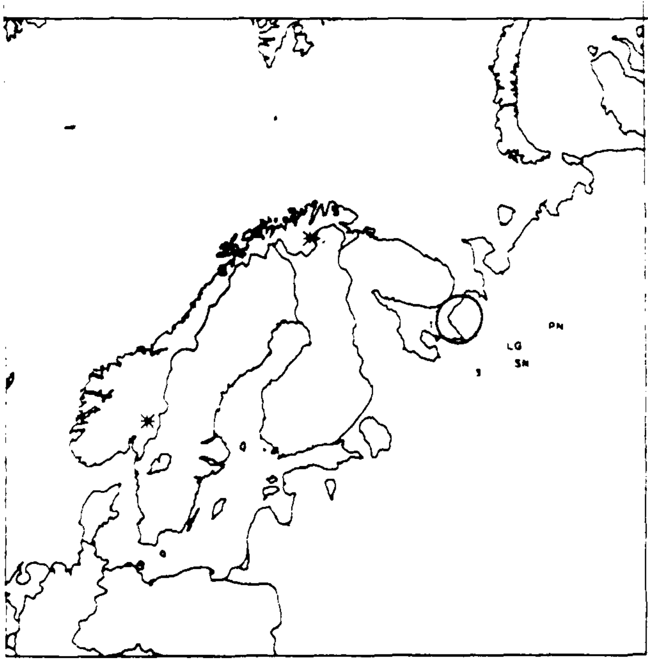
Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
[illegible]	08 22:25	2.0	308	8.5	2.4	46.7	6.5	185	3.33	1	0/0	148677
	08 22:31	3.6	309	9.9	3.0	35.2	10.7	151	3.53	2	0/0	148677
	08 25:54	3.9	310	3.7	1.2	39.4	7.3	858	1.30	1	1/-3	148677

Fri Nov 3 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	08:22:32	[illegible]	278	7.8	1.4	120.4	4.0	2809	5.00	1	0/-3	148677
Pn	08:22:45	3.8	267	7.4	1.8	108.8	11.3	895	3.33	3	0/-2	148657
S	08:22:[illegible]	3.6	233	4.2	0.6	121.3	3.2	1610	3.33	1	0/-1	148677
Lg	08:22:26	1.6	310	3.1	0.4	112.7	6.2	18997	2.50	3	0/-1	148677
S	[illegible]	4.0	309	4.8	0.7	119.9	5.4	2603	3.33	2	0/-2	148677
Sn	08:22:04	3.5	220	3.7	0.7	119.9	4.4	8861	2.14	1	0/0	148657
Lg	08:22:45	3.7	303	3.2	0.3	117.1	3.4	2388	3.53	2	0/0	148657
S	08:22:50	3.9	226	5.4	0.7	128.3	6.4	11944	4.29	3	0/0	148657

[illegible] REALTIME RUN FRI NOV 3 17 05 58 1989





ASSESS #21

MAP DIAGRAM 39.0 DEG ORID 148657 RUN DATE 11/ 3/1989

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Fri Nov 3 08:20:41 1989	67.65	33.83	65.6	61.6	35.6

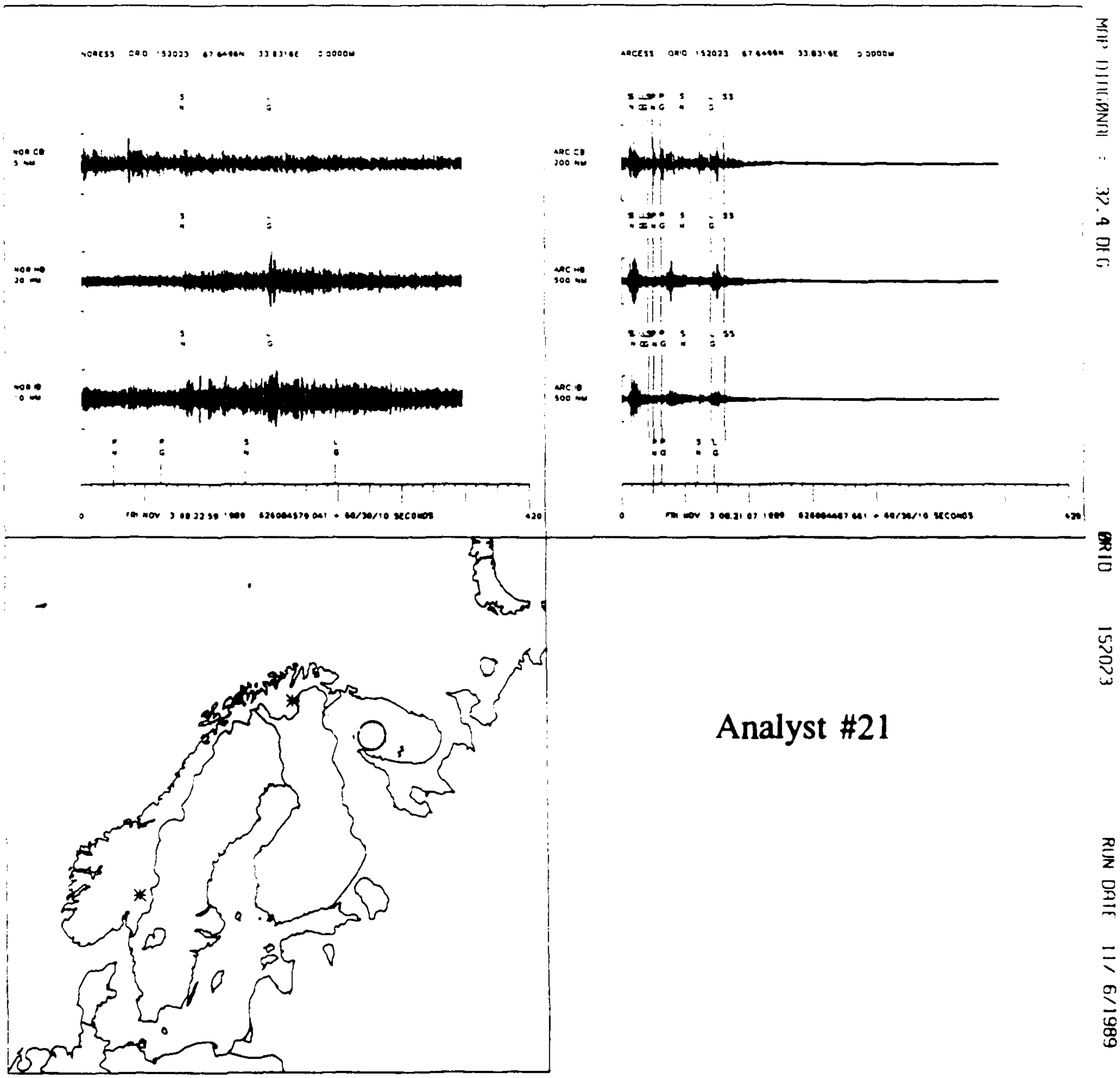
Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A):	89/11/03 08:19:37.336	67.65	33.60	3.50	118.70	80.9	42.2	35.7

. Nov 3 1989 (N)

	Time	Tsd	Bm	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Lr	08:24:32	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	152019
Lg	08:25:54	3.9	310	3.7	1.2	39.4	7.3	858	1.30	1	1/-3	152019

Fri Nov 3 1989 (A)

Ph	Time	Tsd	Bm	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
S	08:21:15	3.6	253	4.2	0.6	121.3	3.2	1610	3.33	1	0/-1	152025
Sn	08:21:17	3.6	253	4.2	0.6	121.3	3.2	1610	3.33	1	0/-1	152019
Lg	08:21:26	1.6	313	3.1	0.4	112.7	6.2	18997	2.50	3	0/-1	152026
Lg	08:21:29	1.6	313	3.1	0.4	112.7	6.2	18997	2.50	3	0/-1	152019
S	08:21:33	4.0	309	4.8	0.7	119.9	5.4	2603	3.33	2	0/-2	152023
Pn	08:21:37	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	152023
Pg	08:21:45	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	152023
Sn	08:22.04	3.5	220	3.7	0.7	119.9	4.4	8861	2.14	1	0/0	152020
Lg	08:22:32	-1.0	-1	-1.0	-1.0	-1.0	-1.0	-1	-1.00	-1	0/0	152023
S	08:22.45	3.7	303	3.2	0.3	117.1	3.4	2388	3.53	2	0/0	152023



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Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Sat Nov 4 07:00:05 1989	51.81	14.37	409.0	125.5	282.3

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(A)	89/11/04 07 00 05 041	51 81	14 37	19 48	202 13	409 0	125 5	282 3

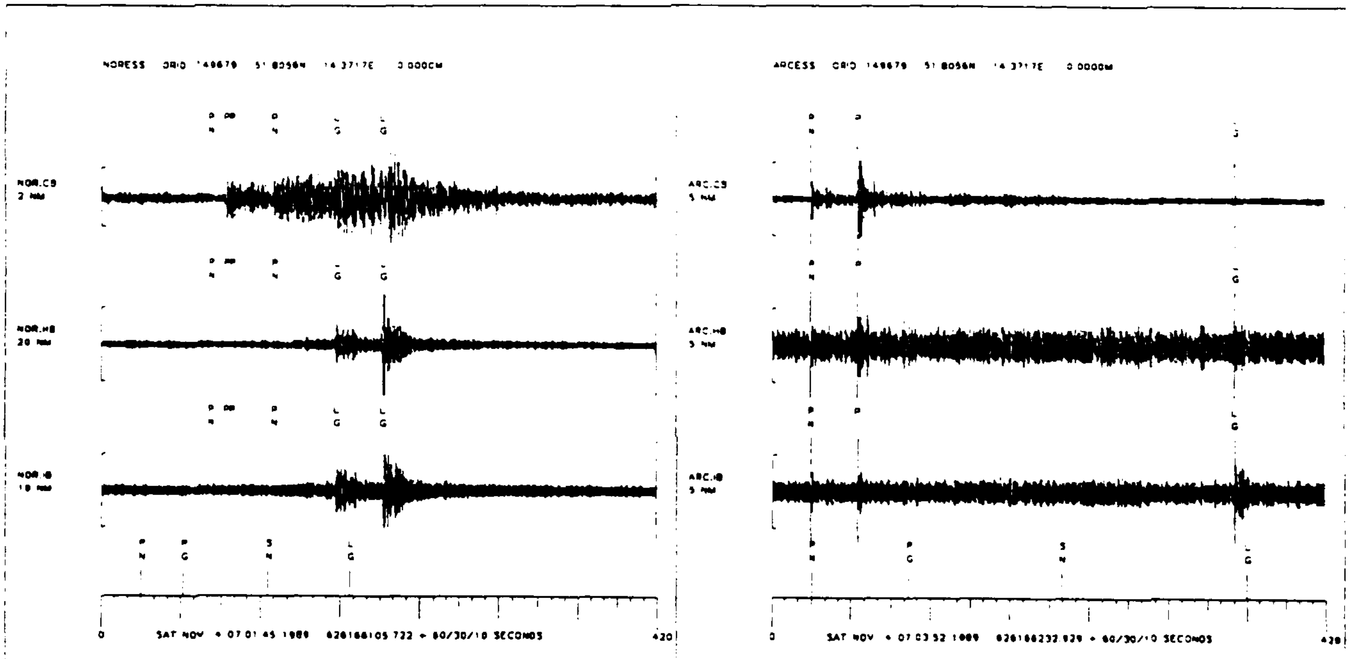
Sat Nov 4 1989 (N)

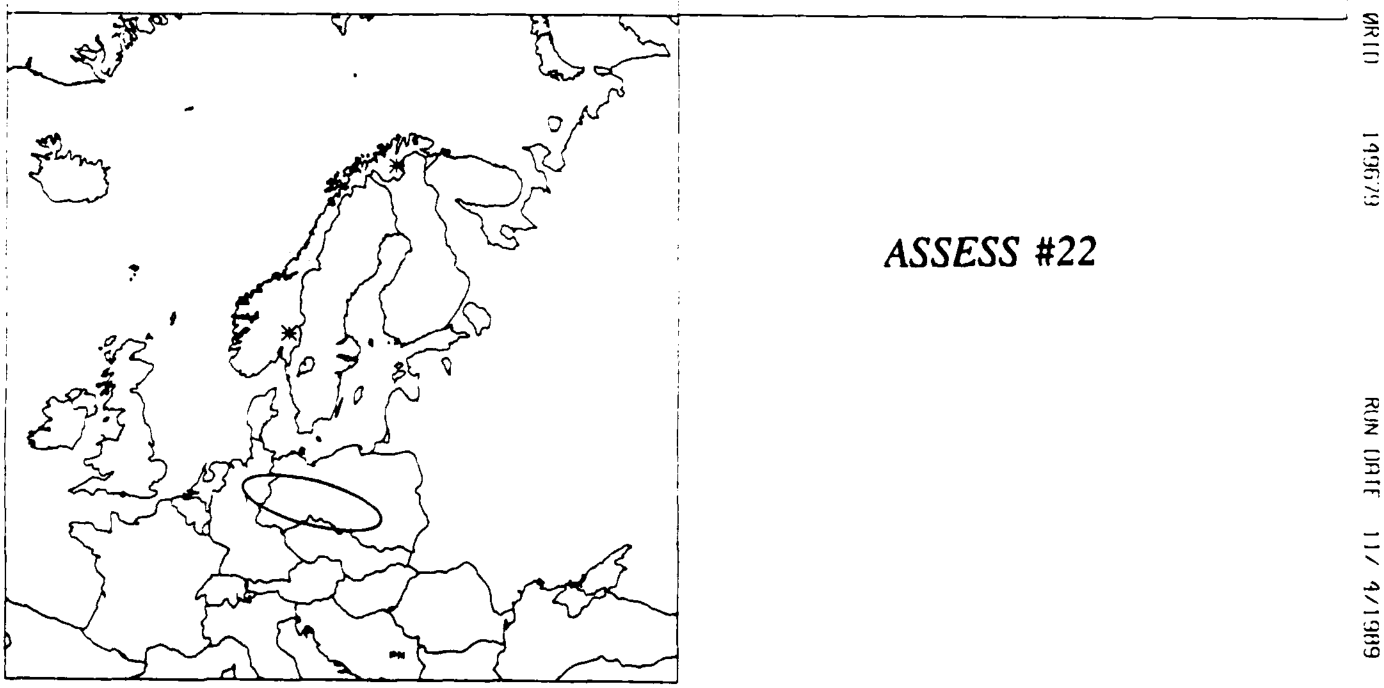
Ph	Time	Tsd	Bmc	Vel	Dvel	Azim	Asd	Stavg	Freq	Fsq	P Spl	Orid
Pn	07 03 37	3 3	294	9 5	1 5	123 3	5 4	54	5 67	2	[illegible]	149674
P	07 03 19	2 3	239	9 7	1 2	125 4	5 7	121	3 57	3	[illegible]	149674
P	07 03 23	3 3	2 1	3 5	1 6	122 7	5 7	45	6 67	2	[illegible]	149674
Pn	07 03 55	4 3	249	3 6	1 3	113 2	4 3	335	10 00	3	[illegible]	149673
Lg	07 04 42	3 9	165	3 9	1 5	125 6	4 2	92	3 75	2	[illegible]	149673
Lg	07 05 17	3 9	269	4 2	3 5	125 5	4 3	39	3 33	2	[illegible]	149674

Sat Nov 4 1989 (A)

Ph	Time	Tsd	Bmc	Vel	Dvel	Azim	Asd	Stavg	Freq	Fsq	P Spl	Orid
Pn	07 04 22	1 5	279	8 5	1 9	187 7	3 1	65	4 29	1	[illegible]	149679
P	07 04 59	1 5	279	9 5	2 2	198 5	5 9	114	3 75	1	[illegible]	149679
Lg	07 09 42	3 8	313	3 0	0 4	207 5	3 1	195	2 50	1	[illegible]	149679

NMMER REALTIME RUN SAT NOV 4 04 26 17 1989





ASSESS #22

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Sat Nov 4 07:01:14 1989	57.96	25.78	174.2	105.8	27.1

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89/11/04 07 01 14 901	57 96	25 79	7 75	104 70	174 2	105 8	27 1

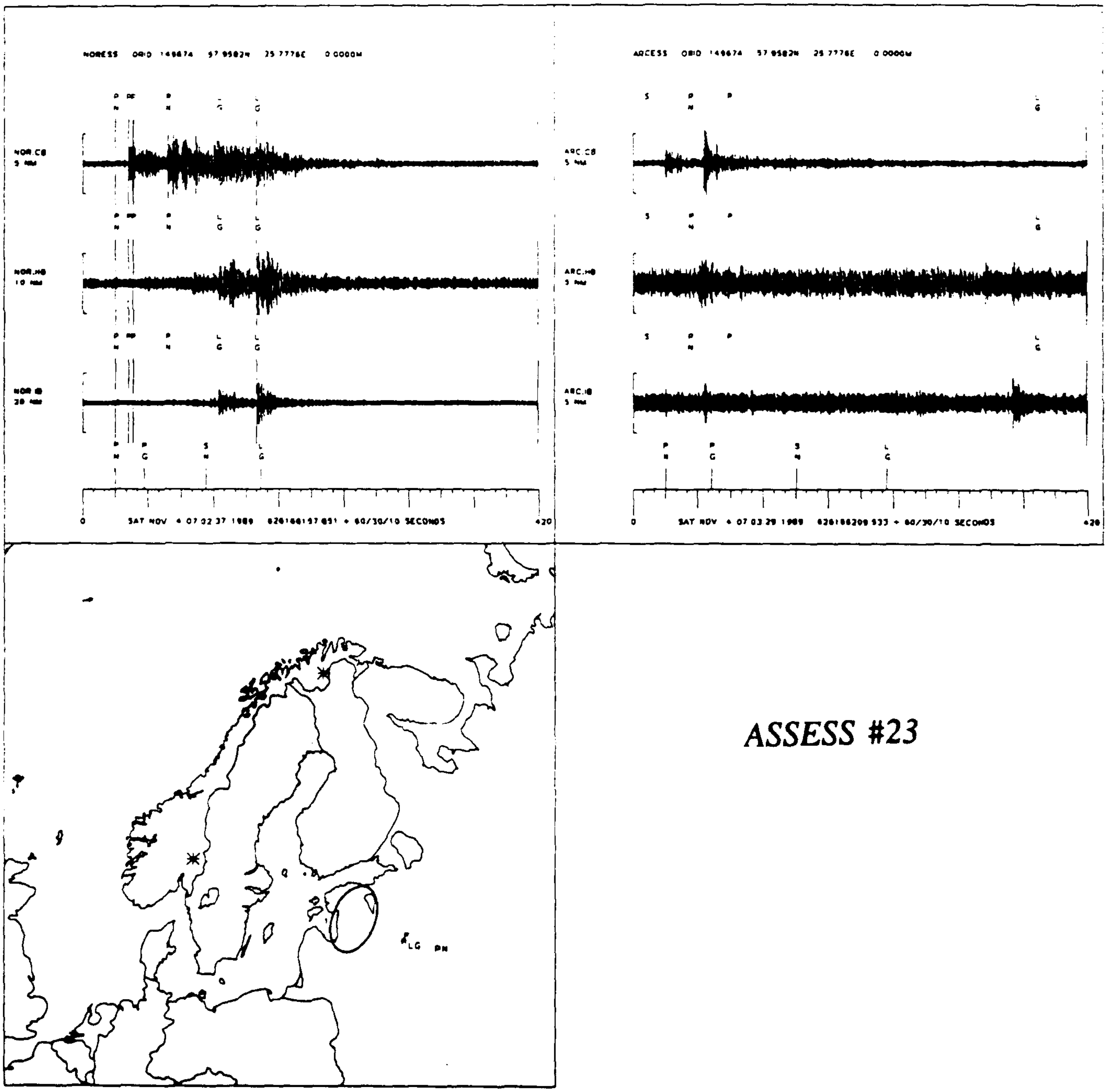
Sat Nov 4 1989 (N)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	07 03.07	3 0	294	9 5	1 5	103.8	5 4	64	6 67	2	1/-1	149674
P	07 03 19	2 0	298	9 7	1 2	105 4	5 7	121	8 57	3	1/-3	149674
P	07 03 23	3 9	292	9 9	1 6	103 7	5 7	75	6 67	1	1/-3	149674
Pn	07 03.55	4 0	238	3 6	1 0	113 1	4 9	105	10 00	3	0/-3	149673
Lg	07 04 42	3 9	265	3 9	0 5	106 6	4 0	82	3 75	2	1/-3	149673
Lg	07 05 17	3 8	259	4 0	0 5	105 5	4 3	98	3 53	2	1/-3	149674

Sat Nov 4 1989 (A)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
S	07 03 42	4 0	310	4 2	1 6	19 5	13 5	625	1 20	2	1/-3	149635
Pn	07.04.22	2 6	279	8 6	1 9	187 7	5 1	65	4 29	1	0/-3	149679
P	07 04 58	2 5	279	8 6	2 0	198 5	5 9	114	3 75	1	0/-3	149679
Lg	07 09 42	3 8	313	3 0	0 4	207 5	3 1	195	2 50	1	0/-3	149679

NMER REALTIME RUN SAT NOV 4 05.50 48 1989



MAP DIAGRAM 35.7 DEG ORID 149674 RUN DATE 11/ 9/1989

ASSESS #23

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Sat Nov 4 07:01:57 1989	59.48	21.95	80.9	27.9	-24.9

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(M):	89/11/04 07:01:14.901	57.96	25.78	7.75	104.70	174.2	105.8	27.1

Sat Nov 4 1989 (M)

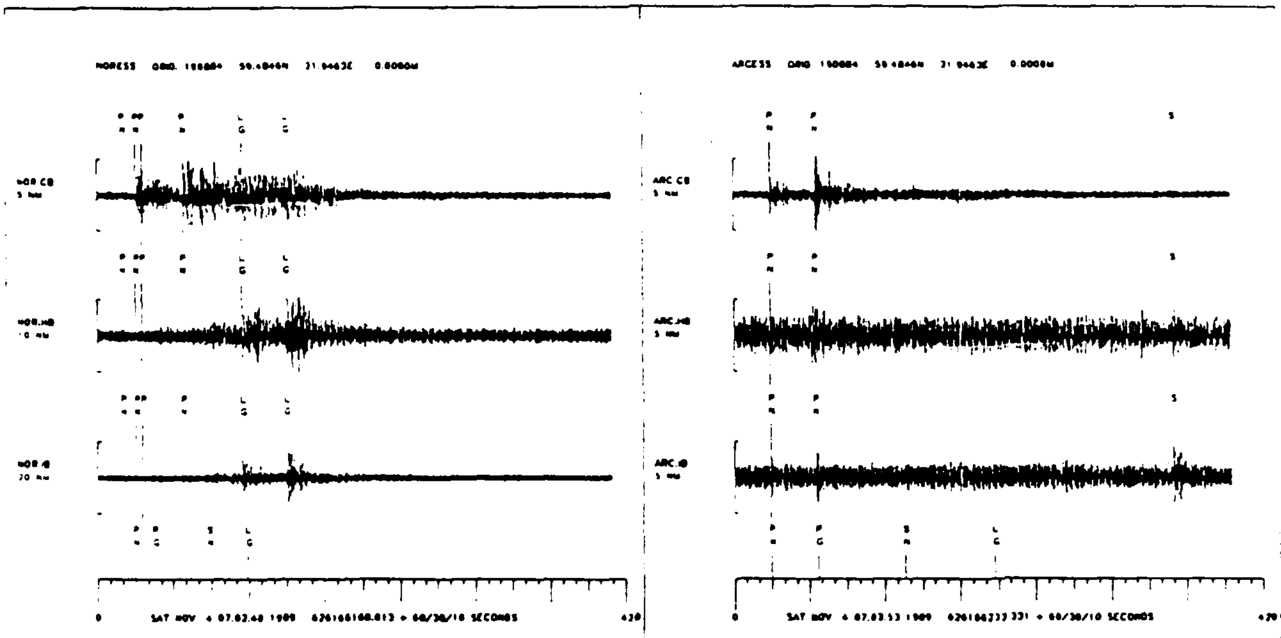
Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	07:03:07	3.0	294	9.5	1.5	103.8	5.4	64	6.67	2	-1/-2	0
Pn	07:03:19	2.0	298	9.7	1.2	105.4	5.7	121	8.57	3	1/-3	190884
P	07:03:23	3.9	292	9.9	1.6	103.7	5.7	95	6.67	2	1/-3	190884
Pn	07:03:55	4.0	298	9.6	1.0	113.1	4.8	205	10.00	3	0/-3	190887
Lg	07:04:42	3.8	265	3.9	0.5	106.6	4.0	82	3.75	2	1/-3	190888
Lg	07:04:43	3.8	265	3.9	0.5	106.6	4.0	82	3.75	2	1/-3	190884
Lg	07:05:17	3.8	269	4.0	0.5	105.5	4.3	98	3.53	2	1/-3	190886

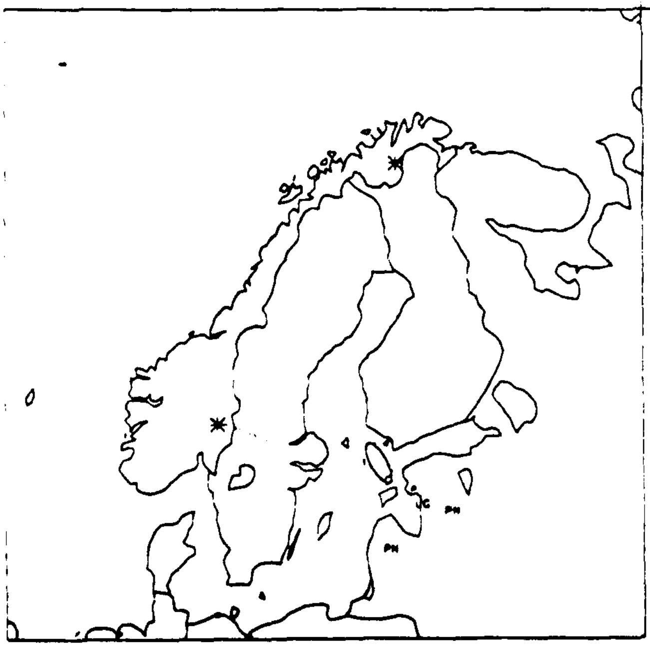
Sat Nov 4 1989 (A)

Ph	Time	Tsd	Bmn	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	07:04:22	2.6	279	8.6	1.9	187.7	5.1	65	4.29	1	0/-3	190884
Pn	07:04:58	2.5	279	8.6	2.2	188.5	5.9	114	3.75	1	0/-3	190887
S	07:09:42	3.8	313	3.0	0.4	237.5	3.1	196	2.50	1	0/-3	152090

Helsinki: 59.74N 21.786E

REALTIME RUN. MON JAN 22 15.28.30 1990





Analyst #23

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Sat Nov 4 07:03:06 1989	59.61	17.29	122.7	65.4	294.2

Site	Origin Time	Lat	Lon	Dist	Azim	SMaj	SMin	Strike
Assess(N)	89/11/04 07 03 06 206	59 61	17 29	3 07	108 33	122 7	55 4	294 2

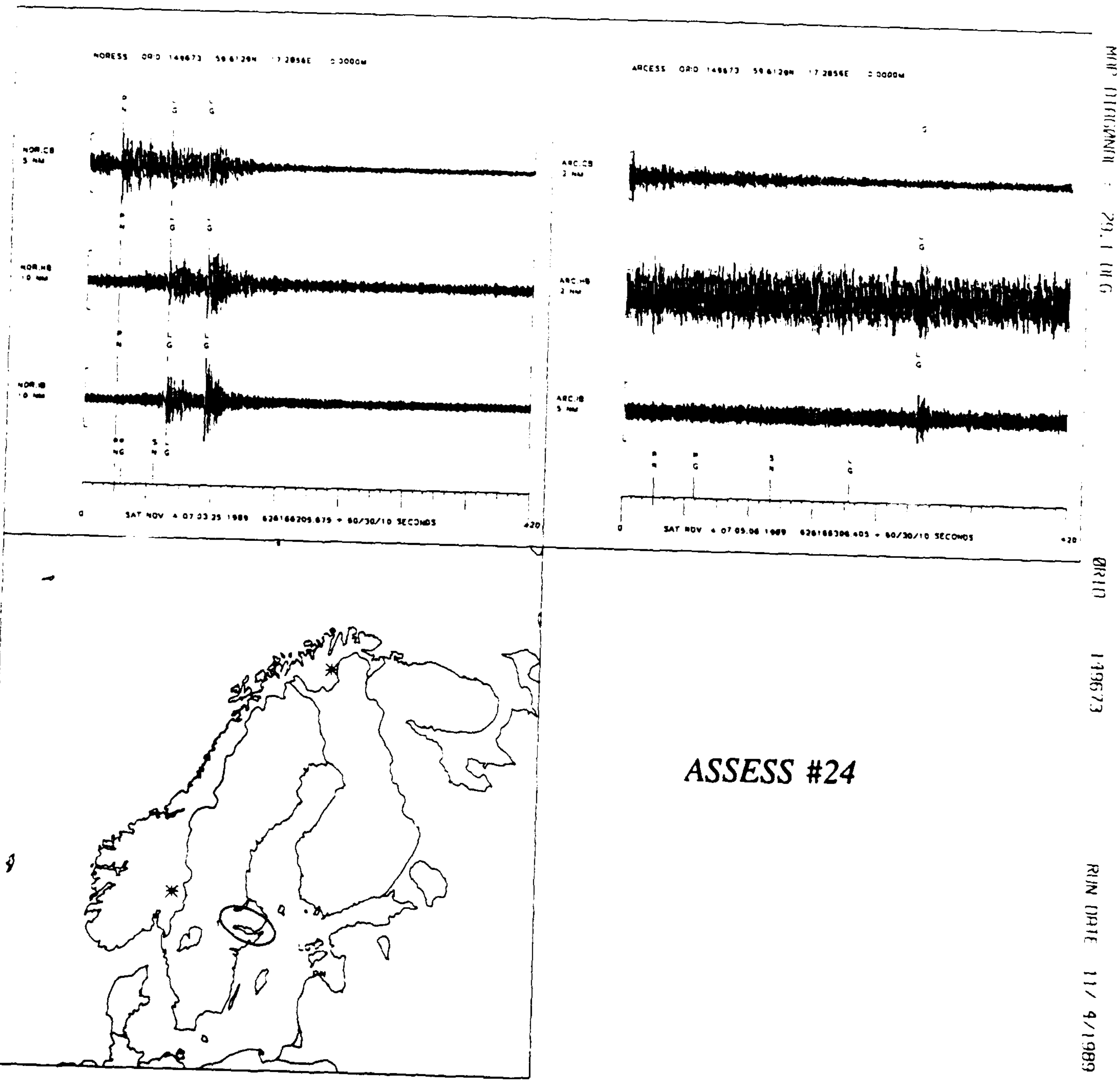
Sat Nov 4 1989 (N)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	07 03 55	4 0	298	9 5	[illegible]	[illegible]	4 9	205	10 00	3	2/3	149573
Lg	07 04 42	3 9	255	3 9	[illegible] 5	124 5	4 0	92	3 75	2	2/3	149573
Lg	07 05 17	3 9	143	4 0	0 5	125 5	4 3	49	3 53	2	2/3	149574

Sat Nov 4 1989 (A)

Ph	Time	Tsd	Bmo	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Lg	07 09.42	3 8	313	3 0	3 4	227 5	[illegible]	136	2 00	1	[illegible]	149679

NMER REALTIME RUN SAT NOV 4 05 28 33 1989



ASSESS #24

Site	Origin Time	Lat	Lon	SMaj	SMin	Strike
Assess:	Sat Nov 4 07:02:34 1989	59.59	21.94	103.0	33.8	-25.1

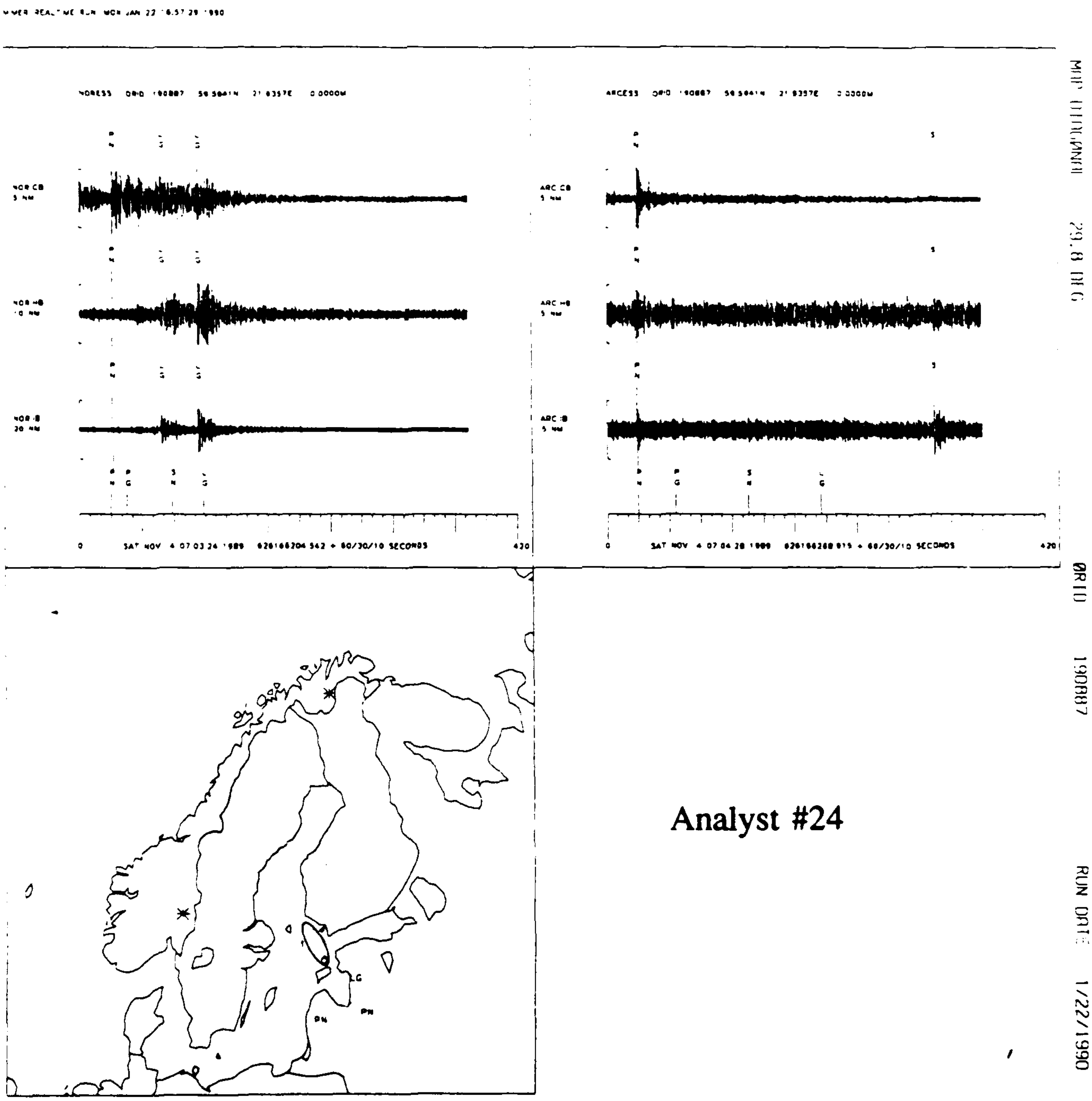
Sat Nov 4 1989 (N)

Ph	Time	Tad	Snr	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	07:03:55	4.0	298	9.6	1.0	113.1	4.8	205	10.00	3	0/-3	190887
Lg	07:04:43	3.8	265	3.9	0.5	106.6	4.0	82	3.75	2	1/-3	190884
Lg	07:05:17	3.8	269	4.0	0.5	105.5	4.3	98	3.53	2	1/-3	190887

Sat Nov 4 1989 A

Ph	Time	Tad	Snr	Vel	Dvel	Azim	Asd	Stavg	Freq	Fkq	P/Spl	Orid
Pn	07:04:58	2.5	279	8.6	2.2	188.5	5.9	114	3.75	1	0/-3	190887
S	07:09:42	3.8	313	3.0	0.4	207.5	3.1	196	2.50	1	0/-3	152090

Helsinki: 59.728N 21.809E



Analyst #24

VII ACKNOWLEDGEMENTS

Design and implementation of the *IAS* was a team effort involving many seismologists and computer scientists at SAIC and several subcontractors. The *ASSESS* expert system for automatic location of regional seismic events was developed by Advanced Decision Systems (ADS), Mountain View, CA under the leadership of Dr. Robert Fung. Significant contributions to the ADS effort were made by Greg Stachnick, Richard Chestek and Sam Owre. The *ScriptMatch* and *SAS* (Script Acquisition System) processes were developed by the contractor team of Ensco, Springfield, VA, and ISX, Thousand Oaks, CA with Dr. Doug Baumgardt (Ensco) as project manager. Ensco also developed the framework for event identification and the *MERSY* process for identifying mine explosions. Key participants in the Ensco/ISX effort included Sam Carter and Kathy Ziegler at Ensco and Karl Kandt, Paul Yuenger, and Paul Kegelmeyer at ISX.

SAIC was prime contractor and system integrator. Task leaders included Dr. Steven Bratt (expert system and knowledge acquisition), Jim Wang (system integration and interactive analysis), Dr. William Farrell (database management and hardware design), Dr. Henry Swanger (interactive analysis and knowledge acquisition), Dr. Jeff Given (system integration and event identification), Cris Kobryn (distributed processing management and knowledge acquisition), Anne Suteau-Henson (signal processing), and Jean Anderson (database management). Key software developers included Ethan Brown (signal processing and expert system integration), Laurie Clow (interactive map displays), Jerry Jackson (distributed processing management) Rick Johnson (interactive map displays), Brian Smithey (interactive analysis), Ed Tharp (user interface and expert system integration), Pete Ware (distributed processing management and interactive analysis). Jon Jump did much of the hardware integration, and Rick Strobridge led the installation of the communication links. Installation and integration of the *IAS* hardware at NDAC was done by NORSAR staff led by Rune Paulsen, and installation and integration at the Center for Seismic Studies was done by Bill Whyte and David Comay of Teledyne Geotech.

The key to the success of the entire project was the early work done by NORSAR to automate the processing of NORESS array data, and their RONAPP program is properly viewed as the first version of *IAS*. Advice and assistance over the course of the project by Dr. Frode Ringdal, Svein Mykkeltveit, Tormod Kværna, and Rune Paulsen of NORSAR is gratefully acknowledged.

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APPENDIX A

DATABASE STRUCTURE FOR *IAS*

The database schema used in *IAS* is an extension of the "Center for Seismic Studies Database Structure Version 2.8" (Brennan, 1987). These extensions are described in this Appendix. Figure A.1 is an entity-relationship diagram. Figures A.2 and A.3 are data flow diagrams that show how the database is updated by individual *IAS* processes. The "pipeline" processes are those active during automated processing of the data. The "knowledge acquisition system" (KAS) processes are those active during and after analyst review of the automatic solutions. Following the figures are tables that are new or changed from Version 2.8. They are presented in the standard format for describing the Center for Seismic Studies Database Structure (e.g., Brennan, 1987).

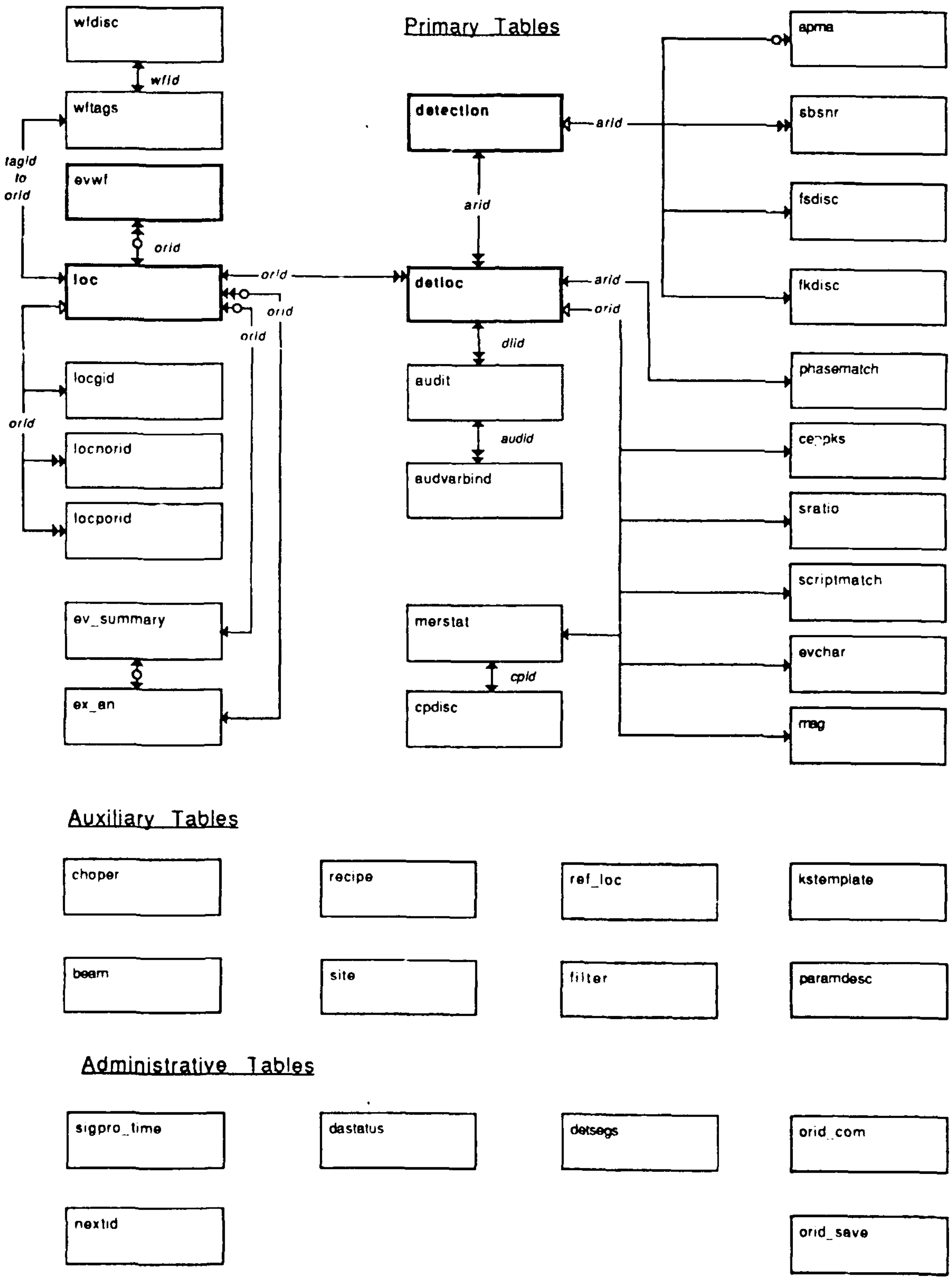

Figure A.1. Entity relationship diagram for database tables used in *IAS* processing.

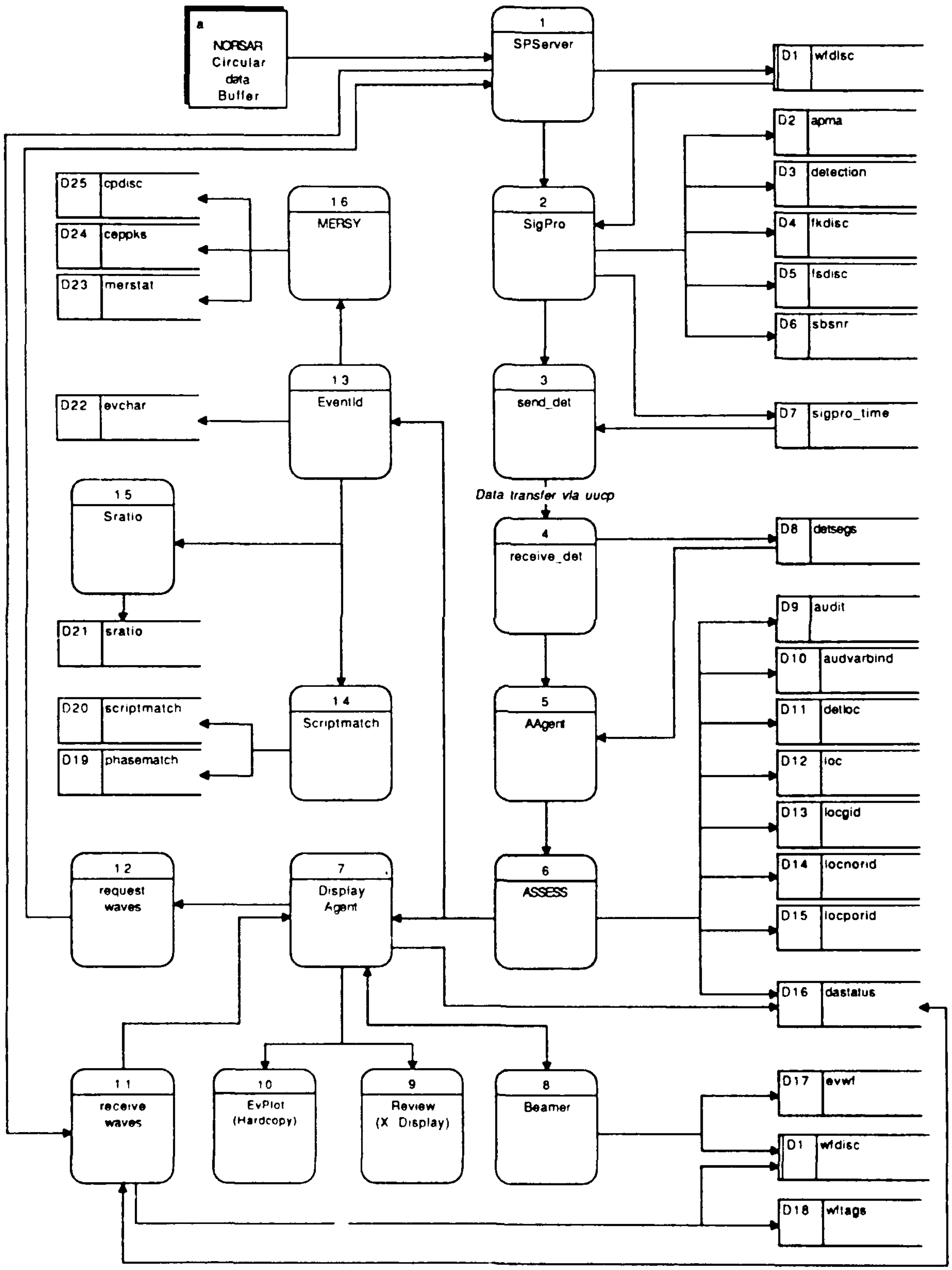

Figure A.2. Dataflow between the *IAS* processes and DBMS during "pipeline" processing.

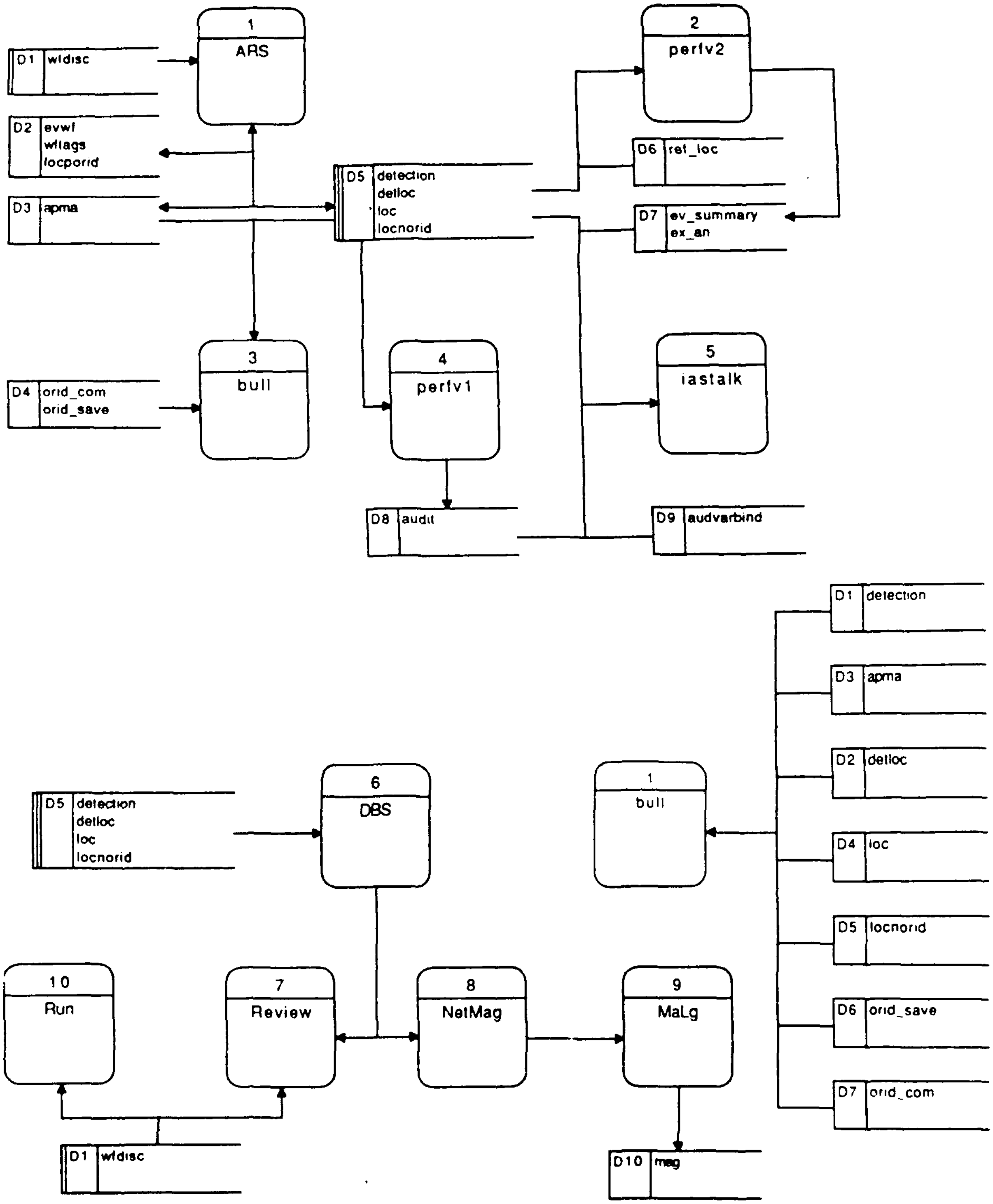

Figure A.3. Dataflow between the *IAS* processes and DBMS during "post-pipeline" and "knowledge acquisition system" processing.

apma				
attribute name	storage type	external format	character positions	attribute description
phase	c8	a8	1-8	phase
arid	i4	i8	10-17	arrival id
freq	f4	f7.2	19-25	frequency
snr	f4	f7.2	27-33	signal to noise ratio
ampp	f4	f7.2	35-41	p phase amplitude
amps	f4	f7.2	43-50	s phase amplitude
amplr	f4	f7.2	52-58	rayleigh phase amplitude
rect	f4	f7.2	60-66	rectilinearity
plans	f4	f7.2	68-74	s phase planarity
planlr	f4	f7.2	76-82	rayleigh phase planarity
hvratp	f4	f7.2	84-90	horizontal to vertical ratio
hvrat	f4	f7.2	92-98	horizontal to vertical ratio
hmxmn	f4	f7.2	100-106	max to min horizontal ratio
inang3	f4	f7.2	108-114	short axis incidence angle
seazp	f4	f7.2	116-122	p phase observed azimuth
seazs	f4	f7.2	124-130	s phase observed azimuth
seazlr	f4	f7.2	132-138	rayleigh phase observed azimuth
inang1	f4	f7.2	140-146	emergence angle
ptime	f8	f15.3	148-162	p phase extraction time
stime	f8	f15.3	164-178	s phase extraction time
auth	c15	fa15	180-194	author
apmarid	i4	i8	196-203	apma recipe id
commid	i4	i8	205-212	comment id
lddate	date	a25	214-238	load date

audit				
attribute name	storage type	external format	character positions	attribute description
audid	i4	i8	1-8	audit id
dlid	i4	i8	10-17	detloc id
audseqnum.b	i4	i8	19-26	audit sequence number
audobjtype	c16	a16	28-43	audited object type
ksid	i4	i8	45-52	knowledge-source id
certainty	f4	f4.2	54-57	certainty factor
validator	c16	a16	59-74	validator
validation	c16	a16	76-91	validation
vdat	date	a25	93-117	validation date
lddate	date	a25	119-143	load date

audvarbind				
attribute name	storage type	external format	character positions	attribute description
audid	i4	i8	1-8	audit id
ksid	i4	i8	10-17	knowledge-source id
var	c16	a16	19-34	variable
is_attr	i1	i2	36-37	is-attribute?
value	c16	a16	39-54	
lddate	date	a25	56-80	load date

ceppks				
attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
sta	c6	a6	10-15	station code
ptyp	c6	a6	17-22	consistent peak type code
pkamp	f4	f7.2	24-30	consistent peak amplitude
pkqf	f4	f7.2	32-38	consistent peak frequency
lddate	date	a25	40-64	load date

cpdisc				
attribute name	storage type	external format	character positions	attribute description
arid	i4	i8	1-8	arrival id
flen	f4	f7.2	10-16	frequency window
lfcut	f4	f7.2	18-24	low frequency cuttoff
fsid	i4	i8	26-33	fourier spectrum id
ceptyp	c6	a6	35-40	cepstrum type, (*e.g.* FC-SNG; MC-SNG)
cpid	i4	i8	42-49	cepstrum id
cprid	i4	i8	51-58	fc recipe id
mxquef	f4	7.2	60-59	maximum frequency rate
nquef	i4	i8	61-68	number of frequency values
nmcoef	i4	i8	70-77	number of coefficients used to create maxentropy cepstra
acoef	f4	f7.2	79-85	a coefficient for nonlinear trend
bcoef	f4	f7.2	87-93	b coefficient for nonlinear trend
ccoef	f4	f7.2	95-101	c coefficient for nonlinear trend
datsw	i4	i10	103-112	data switch
foff	i4	i10	114-123	byte offset in file
dir	c30	a30	125-154	cepstrum directory
file	c20	a20	156-175	cepstrum data file
lddate	date	a25	177-201	load date

ev_summary				
attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
nearsta	c4	a4	10-13	code for nearest station
neardist	f4	f8.3	15-22	distance to closest station
nearaz	f4	f7.2	24-30	azimuth from nearest station
refid	i4	i8	32-39	id of nearest reference point
refdist	f4	i8	41-48	distance to nearest reference point
refaz	f4	f7.2	50-56	azimuth to nearest reference point
grn	i4	i8	58-65	geographic region number
nsta	i4	i4	67-70	# of recording stations
lsta	i4	i4	72-75	# of local observations
asta	i4	i4	77-80	# of reg array observations
rsta	i4	i4	82-85	# of non-array reg observations
tsta	i4	i4	87-90	# of teleseismic observations
ndef	i4	i4	92-95	# of defining phases
adef	i4	i4	97-100	# of assoc nondefining phases
primp	i4	i4	102-105	# of primary phases used
secondp	i4	i4	107-110	# of secondary phases
depthp	i4	i4	112-115	# of depth phases
lddate	date	a25	117-141	load date

ex_an				
attribute name	storage type	external format	character positions	attribute description
forid	i4	i8	1-8	final orid id
eorid	i4	i8	10-17	expert system origin id
ddist	f4	f8.3	19-26	dist between two origins
ddepth	f4	f6.1	28-33	depth difference
dtime	f4	f8.3	35-42	origin time difference
did	c2	a2	44-45	identification difference
dnsta	i4	i4	47-50	difference in recording stations
dlsta	i4	i4	52-55	difference in local stations
dasta	i4	i4	57-60	difference in regional array stations
drsta	i4	i4	62-65	difference in nonarray regional sta
dtsta	i4	i4	67-70	difference in teleseismic sta
dndef	i4	i4	72-75	difference in defining phases
dprimp	i4	i4	77-80	difference in primary phases
dsecondp	i4	i4	82-85	difference in secondary phases
ddepthp	i4	i4	87-90	difference in depth phases
rprimp	i4	i4	92-95	renamed primary phases
rsecondp	i4	i4	97-100	renamed secondary phases
rdepthp	i4	i4	102-105	renamed depth phases
added	i4	i4	107-110	number of added phases
retime	i4	i4	112-115	number of retimed phases
splitev	c2	a2	117-118	split event (y/n)
multev	c2	a2	120-121	multiple events (y/n)
lddate	date	a25	123-147	load date

dastatus				
attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
sta	c6	a6	10-15	station name
status	c9	a9	17-25	processing status
lddate	date	a25	27-51	load date

detsegs				
attribute name	storage type	external format	character positions	attribute description
tstart	f8	f15.3	1-15	beginning time
tend	f8	f15.3	17-31	ending time
pflag	c1	a1	33	processing flag
lddate	date	a25	35-59	load date

filter				
attribute name	storage type	external format	character positions	attribute description
filtid	i4	i8	1-8	filter id
filtyp	c6	a6	10-15	filter type
rsptyp	c3	a3	17-19	response type
hicut	f4	f9.4	21-29	high frequency cut-off
locut	f4	f9.4	31-39	low frequency cut-off
ord	i4	i8	41-48	filter order
hslope	f4	f3.0	50-52	high frequency slope (dB/oct)
lslope	f4	f3.0	54-56	low frequency slope (dB/oct)
ripple	f4	f4.1	58-61	ripple amplitude (dB)
gnorm	f4	f10.5	63-72	normalizing gain
fnorm	f4	f8.4	74-81	normalizing frequency
commid	i4	i8	83-90	comment id
lddate	date	a25	92-116	load date

kstemplate				
attribute name	storage type	external format	character positions	attribute description
ksid	i4	i8	1-8	knowledge-source id
ksname	c64	a64	10-73	knowledge-source name
ksclass	c64	a64	75-138	knowledge-source class
template	a512	a512	140-651	template
nmparams	i2	i4	653-656	number of parameters
lddate	date	a25	658-682	load date

loc				
attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
evid	i4	i8	10-17	event id
date	i4	i8	19-26	julian date
time	f8	f15.3	28-42	epoch time
status	c8	a8	44-51	status of a given origin
lat	f4	f9.4	53-61	estimated latitude
lon	f4	f9.4	63-71	estimated longitude
depth	f4	f9.4	73-81	estimated depth
mb	f4	f6.2	83-88	body wave magnitude
mo	f4	f7.2	90-96	other magnitude
ndef	i4	i4	98-101	number locating detections
nmb	i4	i4	103-106	number of stations for mb
nmo	i4	i4	108-111	number of stations for mo
algid	i4	i8	113-120	algorithm id
smajax	f4	f7.1	122-128	semi-major axis of error
sminax	f4	f7.1	130-136	semi-minor axis of error
strike	f4	f7.1	138-144	strike of semi-major axis
sdobs	f4	f9.4	146-154	std error of obs
szz	f4	f9.4	156-164	depth error
stt	f4	f9.4	166-174	time error
sdmb	f4	f9.4	176-184	std dev of mb
sdmo	f4	f9.4	186-194	std dev of mo
commid	i4	i8	196-203	comment id
etype	c7	a7	205-211	volc., quake, bomb, etc.
auth	i4	f8	213-220	source/originator
moauth	c15	a15	222-236	mo source/originator
lddate	date	a25	238-263	load date

locgid				
attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
gid	i4	i8	10-17	next group id
lddate	date	a25	19-43	load date

locnorid				
attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
norid	i4	i8	10-17	next origin id
lddate	date	a25	19-43	load date

locporid

attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
porid	i4	i8	10-17	previous origin id
lddate	date	a25	19-43	load date

mag

attribute name	storage type	external format	character positions	attribute description
sta	c6	a6	1-6	station name
mag	f4	f4.2	8-11	magnitude
mgtype	c6	c6	13-18	type of magnitude
mgsd	f4	f4.3	20-23	magnitude standard error
amp	f4	f12.4	25-36	amplitude
ampsd	f4	f12.4	38-49	amplitude standard error
freq	f4	f12.4	51-62	frequency
freqsd	f4	f12.4	64-75	frequency error
units	c10	a10	77-86	units of amplitude
evid	i4	i8	88-95	event id
orid	i4	i8	97-104	origin id
commid	i4	i8	106-113	comment id
lddate	date	a25	115-139	load date

merstat

attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
sta	c6	a6	10-15	station code
cpid	i4	i8	17-24	cepstrum id
ceptyp	c6	c6	26-31	cepstrum type code
snrdb	f4	f7.1	1-7	spectrum snr (db)
svar	f4	f7.2	9-15	detrended log spectral variance
skew	f4	f7.2	17-23	detrended spectral skew
skur	f4	f7.2	25-31	detrended spectral kurtosis
cvar	f4	f7.2	33-39	log spectral variance
cskew	f4	f7.2	41-47	cepstral skew
ckur	f4	f7.2	49-55	cepstral kurtosis
lddate	date	a25	57-81	load date

nextid

attribute name	storage type	external format	character positions	attribute description
idtype	c20	a20	1-20	counter name (*e.g.* 'nxarid', 'norid', etc.)
idvalue	i4	i8	22-29	next value of counter
lddate	date	a25	31-55	load date

orid_save				
attribute name	storage type	external format	character positions	attriubute description
orid	i4	i8	1-8	origin id
level	i4	i8	10-17	save level
action	c1	c1	19-19	action flag,confirm data purge
lddate	date	a25	21-45	load date

orid_com				
attribute name	storage type	external format	character positions	attribute description
orid	i4	i8	1-8	origin id
bull_com	c80	a80	10-89	comment for bulletin
misc_com	c80	a80	91-170	other comments
lddate	date	a25	172-196	load date

paramdesc				
attribute name	storage type	external format	character positions	attribute description
paramname	c16	a16	1-16	parameter name
description	c80	a80	18-97	description
lddate	date	c25	99-123	load date

phasematch				
attribute name	storage type	external format	character positions	attribute description
pmid	i4	i8	1-8	phase match id
matchid	i4	i8	10-17	SM/CC matchid
arid	i4	i8	19-26	Detection arrival id
phconf	f4	f8.5	28-35	Phase match confidence
timeex	f8	f15.3	37-51	Expected time of arrival
timesd	f4	f6.2	53-58	Time standard deviation
timeconf	f4	f6.3	60-65	Time confidence
aziex	f4	f6.2	67-72	Expected azimuth
azisd	f4	f6.2	74-79	azimuth standard deviation
aziconf	f4	f6.3	81-86	azimuth confidence
detex	f4	f6.2	88-93	Expected detection snr
detsd	f4	f6.2	95-100	detection snr standard deviation
detconf	f4	f6.3	102-107	detection snr confidence
freqex	f4	f6.2	109-114	Expected frequency
freqsd	f4	f6.2	116-121	frequence standard deviation
freqconf	f4	f6.3	123-128	frequency confidence
velex	f4	f6.2	130-135	Expected velocity
velsd	f4	f6.2	137-142	velocity standard deviation
velconf	f4	f6.3	144-149	velocity confidence
beam201ex	f4	f6.2	151-156	Expected rel.snr,beam 201
beam201sd	f4	f6.2	158-163	standard deviation, beam 201
beam201conf	f4	f6.3	165-170	confidence, beam 201
beam207ex	f4	f6.2	172-177	Expected rel.snr, beam 207
beam207sd	f4	f6.2	179-184	standard deviation, beam 207
beam207conf	f4	f6.3	186-191	confidence beam 107
beam254ex	f4	f6.2	193-198	Expected rel.snr, beam 254
beam254sd	f4	f6.2	200-205	standard deviation, beam 254
beam254conf	f4	f6.3	207-212	confidence, beam 254
beam282ex	f4	f6.2	214-219	Expected rel.snr, beam 282
beam282sd	f4	f6.2	221-226	standard deviation, beam 282
beam282conf	f4	f6.3	228-233	confidence, beam 282
beam310ex	f4	f6.2	235-240	Expected rel.snr, beam 310
beam310sd	f4	f6.2	242-247	standard deviation, beam 310
beam310conf	f4	f6.3	249-254	confidence, beam 310
beam312ex	f4	f6.2	256-261	Expected rel.snr, beam 312
beam312sd	f4	f6.2	263-268	standard deviation, beam 312
beam312conf	f4	f6.3	270-275	confidence, beam 312
pname	c4	a4	277-280	Phase name
lddate	date	a25	282-306	load date
timewgt	f4	f4.1	308-311	relative time weight
aziwgt	f4	f4.1	313-316	azimuth weight
detweight	f4	f4.1	318-321	detection rel snr weight
freqwgt	f4	f4.1	323-326	frequency weight
velwgt	f4	f4.1	328-331	velocity weight
wgt201	f4	f4.1	333-336	beam 201 weight
wgt207	f4	f4.1	338-341	beam 207 weight
wgt254	f4	f4.1	343-346	beam 254 weight
wgt282	f4	f4.1	348-351	beam 282 weight
wgt310	f4	f4.1	353-356	beam 310 weight
wgt312	f4	f4.1	358-361	beam 312 weight

phasematch (continued)				
attribute name	storage type	external format	character positions	attribute description
staid	c5	a5	363-367	station id
pretime	f8	f15.3	369-383	predicted arrival time
pre201	f8	f11.5	385-395	predicted 201 snr
pre207	f8	f11.5	397-407	predicted 207 snr
pre254	f8	f11.5	409-419	predicted 254 snr
pre282	f8	f11.5	421-431	predicted 282 snr
pre310	f8	f11.5	433-443	predicted 310 snr
pre312	f8	f11.5	445-455	predicted 312 snr
timeval	f8	f6.1	457-462	measured real time
azival	f8	f6.1	464-469	measured azimuth
detval	f8	f6.1	471-476	measured detection rel snr
freqval	f8	f6.1	478-483	measured frequency
velval	f8	f6.1	485-490	measured velocity
val201	f8	f6.1	492-497	measured 201 relative snr
val207	f8	f6.1	499-504	measured 207 relative snr
val254	f8	f6.1	506-511	measured 254 relative snr
val282	f8	f6.1	513-518	measured 282 relative snr
val310	f8	f6.1	520-525	measured 310 relative snr
val312	f8	f6.1	527-532	measured 312 relative snr

recipe				
attribute name	storage type	external format	character positions	attribute description
rname	c20	a20	10-29	recipe name
rid	i4	i8	1-8	recipe id
commid	i4	i8	31-38	comment id
datsw	i4	i10	40-49	data switch
foff	i4	i10	51-60	byte offset in file
rectyp	c4	a4	62-65	recipe type
dir	c30	a30	67-96	recipe directory
file	c20	a20	98-117	recipe data file
lddate	date	a25	119-142	load date

ref_loc				
attribute name	storage type	external format	character positions	attribute description
refid	i4	i8	1-8	reference location id
refnam	c16	a16	10-25	reference location name
lat	f4	f9.4	27-35	latitude
lon	f4	f9.4	37-45	longitude
descrip	c80	a80	47-126	description
lddate	date	a25	128-152	load date

sbsnr				
attribute name	storage type	external format	character positions	attribute description
arid	i4	i8	1-8	arrival id
chid	i4	i8	10-17	channel operation id
stav	f4	f11.5	19-29	max short term average in window
ltav	f4	f11.5	31-41	long term average at detection time
lddate	date	a25	43-67	load date

scriptmatch				
attribute name	storage type	external format	character positions	attribute description
matchid	i4	i8	1-8	SM/FCC match id
orid	i4	i8	10-17	Assess origin id
mconf	f4	f7.5	19-26	Overall match confidence
pconf	f4	f7.5	28-34	Primary match confidence
sconf	f4	f7.5	36-24	Secondary match confidence
mlat	f4	f7.5	44-52	Match latitude
mlong	f4	f7.5	54-62	Match longitude
relabeled	i2	i4	64-68	Number of relabeled phases
missing	i2	i4	70-74	Number of missing phases
textexpl	a25	c25	76-100	Short text explanation
lddate	c25	a25	102-126	Load date

sigpro_time				
attribute name	storage type	external format	character positions	attribute description
sta	c6	a6	1-6	station code
proctime	f8	f15.3	8-22	consistent peak type code
lddate	date	a25	24-39	load date

wftags				
attribute name	storage type	external format	character positions	attribute description
tagse	i4	i8	1-8	tag switch
tagid	i4	18	10-17	tag id (i.e. orid)
wfid	i4	i8	19-26	waveform id
lddate	date	a25	28-52	load date

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT:

4. PERFORMING ORGANIZATION REPORT NUMBER(S): SAIC-90/1437

5. MONITORING ORGANIZATION REPORT NUMBER(S): Distribution Unlimited
Approved for Public Release

6a. NAME OF PERFORMING ORGANIZATION: Science Applications International Corporation

6b OFFICE SYMBOL (If applicable):

7a. NAME OF MONITORING ORGANIZATION: Defense Advanced Research Projects Agency (DARPA)

6c ADDRESS (City, State, and ZIP Code): 10260 Campus Pt. Drive
San Diego, CA 92121

7b. ADDRESS (City, State, and ZIP Code): DARPA
1400 Wilson Boulevard
Arlington, VA 22209

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: DARPA

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: MDA903-87-C-0037

8c. ADDRESS (City, State, and ZIP Code): 1400 Wilson Boulevard
Arlington, VA 22209

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11 TITLE (Include Security Classification): Intelligent Array System - Final Technical Report

12 PERSONAL AUTHOR(S): Bache, Anderson, Baumgardt, Bratt, Farrell, Fun, Given, Henson, Kobryn, Swanger, Wang

13a. TYPE OF REPORT: Final Technical

13b TIME COVERED: FROM 1 Apr 87 TO 30 Sep 90

14 DATE OF REPORT (Year, Month, Day): 1990 October

15. PAGE COUNT:

16 SUPPLEMENTARY NOTATION:

17 COSATI CODES

FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Seismology, knowledge-based systems, signal processing, seismic event location, UNIX distributed processing

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This final technical report includes a short Executive Summary which summarizes important management and administrative aspects of this 42-month project, including a brief chronology and an accounting for the funds by major cost category. The rest of the report presents a detailed description of the major product of this project, a computer hardware/software system called the Intelligent Array System (*IAS*). The *IAS* processes data from two high-frequency arrays (NORESS & ARCESS) in Norway to detect, locate and identify seismic events. The *IAS* computers and functions are distributed between the NORSAR Data Analysis Center (NDAC) near Oslo and the Center for Seismic Studies (Center) in Arlington, VA. The *IAS* modules at NDAC automatically retrieve data from a disk buffer, detect signals, compute signal attributes (amplitude, slowness, azimuth, polarization, etc.), and store them in a commercial relational database management system (DBMS). *IAS* makes scheduled (e.g., hourly) transfers of the

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

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data to a separate DBMS at the Center. Arrival of new data automatically initiates a "knowledge-based system" (KBS) which interprets these data to locate and identify (earthquake, mine blast, etc.) seismic events. This KBS uses general and area-specific seismological knowledge represented in rules and procedures. For each event, unprocessed data segments (e.g., 7 minutes for regional events) are retrieved from NDAC for subsequent display and analyst review. The interactive analysis modules include integrated waveform and map display/manipulation tools for efficient analyst validation or correction of the solutions produced by the automated system. Another KBS compares the analyst and automatic solutions to mark overruled elements of the knowledge base. Performance analysis statistics guide subsequent changes to the knowledge base so it improves with experience.

The *IAS* is implemented on networked Sun workstations, with a 56kbps satellite link bridging the NDAC and CSS LANs. The software architecture is modular and distributed, with processes communicating by messages and sharing data via the DBMS. The *IAS* processing requirements are easily met with major processes (i.e., signal processing, expert system, DBMS) on separate Sun 4/2xx workstations. This architecture facilitates future expansion.