APT89

1989 ARCHEAN-PROTEROZOIC TRANSITION EXPERIMENT

Submitted By

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PASSCAL Data Report 91-003

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Data Report
for
The 1989 Archean-Proterozoic Transition Experiment (APT89)

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for the
PROJECT SCIENCE TEAM

***** PASSCAL DATA REPORT #91-003 *****

ABSTRACT

This report describes the data collected during the Archean-Proterozoic Transition teleseismic experiment (APT89) which operated from June through October 1989. Of the 25 3-component stations installed along a 1500 km transect from western Ontario to eastern Wyoming, 10 were continuously recording PASSCAL instruments with either Kinemetrics SV-SH 5 second or Guralp CMG-3 30 second seismometers and 15 were triggered University of Wisconsin instruments with 1 second Hall-Sears HS10 sensors. A total of 324 teleseismic and regional events with body wave magnitude greater than 5.1 have been extracted from the entire data set. The data format and organization, calibration, and auxiliary information are discussed.

1. Introduction

The 1989 Archean-Proterozoic Transition Experiment (APT89) was designed to study the changes in seismological properties of the crust and upper mantle across a major geological transition: the Archean rocks of the Canadian Shield and the Proterozoic rocks of the North American Central Plains. The deployment lasted from June 8 to October 31 and involved at most 25, three-component, intermediate and short period portable stations arranged in two approximately linear segments which intersected the two permanent RSTN stations RSON in Red Lake, Ontario and RSSD in the Black Hills of South Dakota (see map).

The station spacing was approximately 50 km in Canada and eastern Minnesota, and 100 km in the United States. The denser configuration in the north was chosen to take advantage of the greater geologic control offered by stations on or near the basement so one could test whether the visible changes in geology would be mirrored by changes in teleseismic P and S arrivals. The larger spacing in the U.S. was primarily to assure that there would be enough stations to cover the transition from the Canadian Shield through the Trans-Hudson and then back onto the Wyoming Craton.

1.1. Instrumentation

Of the 25 portable stations, there were two types of seismographs deployed. Ten of them were the PASSCAL data loggers with either Kinemetrics SV-SH 5 second sensors or Guralp CMG-3 30 second sensors which continuously recorded at (usually) 10 samples/second to an external disk. On average, about half of the PASSCAL instruments used GOES receivers and the rest used OMEGA receivers as external time references. The other fifteen instruments were University of Wisconsin data loggers with Hall-Sears HS10 1 second sensors. Because of data storage limitations, the UW package operated in a triggered mode which, after sensing a teleseismic P arrival, recorded at 25 samples/second for 20 minutes so that the accompanying S phases would also be captured. All of the UW instruments used the OMEGA signal as their external time reference. (In addition, for about half of the experiment, the permanent RSTN stations RSON and RSSD were operational and may be important as reference data sets. The data from these stations are not included in this release).

The different portable packages were alternated spatially for two apparently unrelated reasons. The first was simply so that any trends in the data along the transect could not be attributed to differences in the instrument types. The second was that the scientific demands of this experiment presented both packages with varying degrees of uncharted territory. In other words, if one instrument type was to perform less satisfactorily under given conditions, then hopefully the adjacent stations would escape this calamity and the desired spatial coverage would at least be partially intact. In addition to the above concerns, for a brief interval near the beginning of the experiment, there were two sites at which both packages were operating simultaneously. Although this further measure of quality control made my life miserable for at least a year after the data collection concluded, it helped bring to light several problems, particularly in the timing and calibration, which I hope have improved this data set as well as those yet to be collected in future experiments.

1.2. Seismometer Installations

The installations varied as much as the station spacing and for basically the same reasons. Depending on the site conditions, the Hall-Sears seismometers either were buried under several feet of soil or were plastered to bedrock and then covered with soil. These stations were relatively simple to install and, except for periodic visits by curious animals and a heightened sensitivity to telluric currents, performed quite well.

As for the longer period Kinemetrics and Guralp sensors, the greater temperature sensitivities made thermal stability an additional concern for these installations. In the U.S. where there was plenty of unconsolidated sediments, the seismometers were placed in rectangular holes dug several feet into the ground. A 100 quart cooler with its bottom removed was placed on the undisturbed floor and covered by a larger plywood enclosure (also beneath ground level) in which eight inches of removable R-10 insulation was fit above the top of the cooler. The cooler served well as a sturdy, yet accessible enclosure for the seismometers which did require regular adjustment. The sensors were coupled to the ground either with four inch tapered brass spikes driven into the soil and placed under each seismometer foot or with a layer of quick-dry cement which covered the exposed ground inside the cooler. Due to rocks in the soil, it was often not trivial to install the spikes so that they were not only under the individual feet and at the correct geographic orientation, but also reasonably vertical so that the sensors would not slide off. When these problems could not be overcome, the more traditional cement flooring was resorted to. The problem with these sites, as in similar portable installations in the past, is that they suffered from incessant tilting of the sensors due to either heaving of the entire slab or settling of the pointy feet into the surface. In Canada, where there were usually no sediments in which to dig in, the seismometers were placed directly on a horizontal section of unfractured bedrock. The bottomless cooler was placed over them and fastened to the rock with spray-foam insulation. A larger plywood enclosure was built around the cooler and the whole structure surrounded by dirt. Again, eight inches of insulation was placed inside the plywood enclosure above the cooler.

Despite the rather labor intensive nature of such installations, the effort seems to have been worthwhile. Although the temperature was not monitored continuously, periodic measurements indicated that while the outside temperature ranged from about 30 degrees Celsius in the summer to about 0 degrees by late October, the temperature inside the coolers went from about 20 to 10 degrees. The ten degree range inside a portable installation is an important figure because earlier experiments had shown that the Kinemetrics vertical mass would drift from center to "red-line" over such a temperature range. (It should be noted that Kinemetrics has since addressed the problem and have reportedly changed the material used in the suspect component to one with a lower coefficient of thermal expansion (John G. Diehl, personal communication)). In this experiment each site was visited every seven to fourteen days, so that these seasonal variations were easily kept in check, but our experience may hold some relevance for more remote deployments of other temperature sensitive seismometers where such short service intervals may not always be possible.

1.3. The Data Sets

The data from APT89 have been divided into two sets. The Event Data Set contains all teleseismic and regional events with body wave magnitude greater than 5.1, the calibration pulses and the auxiliary information included or discussed in this report. These data have been checked extensively for switched components, flipped polarities, timing errors, instrument malfunction as well as other quality control concerns and corrected whenever possible. This set is about 685 Megabytes in volume and should be considered the primary release for APT89. The Raw Data Set contains all of the University of Wisconsin triggers and all of the PASSCAL continuous data. Due to the large volume of this set (6.0 Gigabytes), quality control measures were limited only to those recognized and logged by the field crew (e.g. OMEGA 10 seconds off, seismometers hooked up to the wrong channels, buggy EPROMS causing the clock to not advance, etc.). For these reasons, the Raw Data Set should be considered just that and not much more of it will be mentioned in this report. However, it will be available through IRIS, but as a separate release.

2. Description of the Event Data Set

The Event Data Set is divided into four subdirectories: apt89/EVENT, apt89/CAL, apt89/TIME and apt89/INFO. The EVENT directory contains the events above body wave magnitude 5.1 which were extracted from the entire set of APT89 seismograms. The CAL directory contains estimated instrument parameters as well as the calibration pulses themselves. The TIME directory contains the estimated timing errors for the PASSCAL data. The INFO directory contains this document and accompanying map as well as the station and event information of Tables 1 and 3 in an ASCII format more easily accessible by user programs. The structure and format of each of these are discussed below.

2.1. Extracted Events

The event list used for the extraction is shown in Table 3 and was last updated by the National Earthquake Information Center in March 1991. Due to slight changes in magnitude which occurred during periodic updates, some events in this list may actually be smaller than 5.1. There are also a few which are less than 5.1, but which triggered several University of Wisconsin stations, and therefore possessed decent signal-to-noise. In such cases, the corresponding PASSCAL data were also extracted. While an exhaustive search for such "clusters" has not been carried out in preparing this list, it has been our experience that teleseisms below the 5.2 threshold, unless they either are relatively close or have favorable radiation patterns, generally will have poor signal-to-noise.

The time window used for the extraction was five minutes before the PREM-predicted direct P arrival time and 15 minutes after. This was accomplished using a nice code written by Michael Acierno at DTM, and would have been an intractable task without it. For the continuous PASSCAL data, the resulting "sliced" files were exactly 20 minutes long unless there were gaps at either end of the desired time window. For the UW data, any triggers which occurred at any time within the desired window were extracted. In cases where there was more than one trigger occurring during the time interval, any time gaps in the seismic data were zero-filled and the multiple files concatenated.

Each of these files are named according to the following format:

yyddd/hh.mm.ss.stnm.c.sac

where *yyddd/hh.mm.ss* is the origin time of the event from Table 3, *stnm* is the four-letter station name from Table 1, and *c* is the channel number. It is important to note that the time fields given in the filename do not refer to the start time of the file as is often the case in other data distributions. Each letter in the station name is chosen based upon the following convention: the last letter describes what kind of seismograph was used at that site (i.e. *r* for PASSCAL/Reftek and *w* for University of Wisconsin), the third is the first letter of the state or province in which the station was located (i.e. *o* Ontario; *m* Minnesota; *n* N. Dakota; *s* S. Dakota; *w* Wyoming), and the first two letters abbreviate the nearest town or landmark.

The nominal orientations of the channel numbers are as follows: *1,4* up positive; *2,5* north positive; *3,6* east positive. However, because the magnetic declinations were not exactly known at the time of installation and the mosquitos and black flies were not quite as thick in October as in June, the orientation of the horizontal sensors were remeasured when each site was dismantled. Using these values and the magnetic declinations and drifts from a declination map [The Magnetic Field in the U.S., 1985 Declination Chart. USGS Geophysical Investigations Map GP-986-D], the geographic orientations are calculated and listed in Table 1. Also in this table are the orientations of the vertical sensors which have been assumed to be exactly vertical (0.0 degrees) unless there was a flip in polarity (180.0 degrees).

All of the data have been converted into SAC binary format and put into individual *stnm* directories. In addition to the waveforms, each of these station directories contain a SAC macro named *stnm.sachdr.macro*. These macros contain all of the commands needed to change the following information in the SAC header: event location, station name, station location and seismometer orientation. All of these macros have been run on the data, but should this information change in the future, they may be handy as repair routines. One additional note about the orientations is that in cases where the east component was not exactly orthogonal to the north, the SAC header value "cmpaz" was changed so that it would be exactly orthogonal to the the north "cmpaz". If this is not your favorite solution to the problem of rotating non-orthogonal data, then these values may also be changed to suit your needs.

2.2. Calibration

Because of the large variation in site conditions and the differences among the various packages used, the accurate calibration of the APT89 data is especially crucial. All of the instrument parameters needed for APT89 are included in the subdirectory *CAL/Summary*. In this directory, there is a file called *README_CAL* which describes the different files as well as some important instrument anomalies which were unearthed in verifying the responses of the different packages. In the absence of such instrument malfunction, there are basically four types of instrument parameters needed to recover the true ground motion from the waveform data:

(1) allw.filt.pole0 [2]

These two files contain the poles and zeros for the highpass and lowpass filters found in the University of Wisconsin instruments. An important note is that station "crow" contained a highpass filter which differed from all of the other UW data. This is why there is a separate file called "crow.filt.pole0". In any event, the format is compatible with the SAC routine "transfer".

(2) allr.fir.sample_rate.alpha [3]
These three files contain the FIR coefficients which were used by the PASSCAL data-loggers at the indicated sampling rates. They are in SAC alphanumeric format.

(3) stnm.pole0.channel# [6]
These six files contain the poles and zeros for the Guralp CMG-3 which were used at station efor (channels 1-3) and station rlor (channels 4-6). An important note is that the constant given for the vertical component ("rlor.pole0.4" and "efor.pole0.1") does not account for the polarity flip relative to all of the other APT89 data. Instead, this has been accounted for in the SAC header value "cmpinc" which has been set to 180 degrees for these data. The format is compatible with the SAC routine "transfer".

(4) station_name.parms [24]
These 24 files contain the set of instrument parameters free period (seconds), damping (fraction of critical), and magnification (volts/meter/second). These parameters were determined by inverting the calibration pulses collected at each station. A "+" has been placed next to those sets of estimated values which appear to be anomalous.

The first two are relatively self-explanatory, but in order to more fully appreciate the numbers contained in the other two summary files, some additional explanation may be useful.

The active Guralp-CMG sensors were calibrated in the field, but because of limitations in the period of the input signal, the resulting pulses overlapped each other in time. These pulses were not used, except to confirm that the parameters given on the manufacturer's calibration sheets would generate reasonable matches to these convolved pulses. Nonetheless, the pulses from "efor" (there are no calibration pulses for the Guralps when they were at "rlor") are also included in this release for those who may be interested. For the rest of us, the aforementioned set of files containing the poles and zeros can be used to correct these data.

All of the passive electromagnetic seismometers were initially tuned in the laboratory to the following nominal parameters:

Seismometer Parameters Set in the Laboratory		
Seismometer	Free Period (sec)	Fraction Critical Damping
Hall-Sears (UW)	1.0	0.5
Kinemetrics (PASSCAL)	5.0	0.7

Once they were removed from the serenity of the indoors and chucked into the dirt, each station was periodically calibrated. Every three days, the UW packages were injected with a pseudo-random sequence 330 seconds long followed by a 330 second long sequence of current steps. At the time of the experiment, the PASSCAL data-loggers did not yet have the capability to automatically calibrate. In lieu of this, each station was calibrated twice whenever it was visited (every 7-14 days): once when the field crew first arrived (provided the instrument was still recording), and again after the data were dumped and the sensor mass positions checked and adjusted, if necessary. Each seismometer was injected with alternating steps in current for a total duration of about 200 seconds. All of these calibration intervals are organized as follows:

yyddd/hh.mm.ss.stnm.c.sac

where *yyddd/hh.mm.ss* is the start time of the file, *stnm* is the four-letter station name, and *c* is the channel number. As in the extracted events, they are in SAC binary format and collected into *stnm* subdirectories.

For the stations deployed with passive sensors, the response of the seismographs to these steps in current were used to obtain the three seismometer parameters free period, fraction critical damping and magnification. The fit of the recorded pulses to synthetic pulses was accomplished using an unpublished code of D. B. Harris of Lawrence Livermore National Lab. (I would like to thank him personally for making at least one phase of this data preparation remarkably stress free.) From each calibration interval, as many usable pulses as possible were extracted and individually inverted for. An average was then taken of the resulting parameters for each channel during that interval. While the values for the frequency dependent parameters (free period and damping) can be quickly confirmed by comparing the observed waveform with the synthetic, converting the amplitude dependent term (magnification) into actual ground motion has historically been a non-trivial goal of seismologists. This study is no exception and in some sense requires a leap of faith. The reason for this is that although the current fed into each sensor is known for both packages, the actual constants needed to transform this current into an acceleration of the mass are not. However, the following nominal values for these constants are known and, together with the known input currents, can be used to calculate the magnification for each sensor.

Seismometer		Cal Coil Force Constant (Newton/Amp)	Effective Mass (kg)
Hall-Sears HS10	vert	160.0	0.940
	horiz	160.0	0.936
Kinemetrics SV/SH	vert	0.12	1.36
	horiz	0.08	1.10

This document has not been burdened with the large volume of estimated parameters for each station. Rather, these results are collected in ASCII files called *CAL/Summary/stnm.parms*. The FILENAME column indicates when the calibration was performed as well as what file contains the pulses. The PULSES column indicates how many were used in computing the average values for that row and often highlight some of the less reliably estimated parameters. The mAMP column is the current which was fed into each sensor measured in milliamps. In general, the injected current was unchanged for each package, except for some of the earlier PASSCAL pulses. The initial value of 0.25 milliamps was found to be too wimpy to overpower the microseismic noise and was later changed to 0.50 milliamps. The implication of this is that these smaller pulses may not be as reliably estimated as the later ones, although toward the end of the experiment, the microseisms were once again becoming a nuisance even for the larger pulses.

One Final Caveat

As previously mentioned, a "+" has been placed next to the sets of parameters which should be considered suspect. Although readers of this manuscript have been spared the descriptions of these problems, they can be found in the *README_CAL* file. However, the information used in compiling this list came from the calibration parameters only and not through an exhaustive search of the entire waveform data set. Therefore, it should not be considered a synopsis of possible defects in the data. There are many other anomalies present which have not been discussed due to limitations in the scope of a report of this kind. For example, it has been assumed that a user is able to recognize when a seismometer is hitting the stop (e.g. EVENT/diwr/89276/23.09.53.diwr.2.sac) or when a flaky connection is corrupting the signal (e.g. EVENT/naor/89189/10.33.07.naor.1.sac; EVENT/rlor/89220/07.59.06.rlor.4.sac) or when an instrument has just gone bonkers (e.g. EVENT/naor/89226/17.51.08.naor.?.sac; EVENT/fvnr/89298/20.29.00.fvnr.?.sac). In addition to these flagrant weirdnesses, there are sometimes more subtle malfunctions (e.g. EVENT/glww/89170/16.00.47.glww.?.sac) which simply cannot be culled entirely from a dataset of this size in a realistic time frame, but which nonetheless await the opportunity to confound the unwary. The purpose of this discussion is not to scare one away from these data, but rather to insure that they be used with a caution befitting the fruits of any prototype experiment.

2.3. Timing

As mentioned in the introduction, two types of reference time signals were used in APT89: GOES and OMEGA. Table 2 lists the clock types used at each station. It should be noted that the reception and interpretation of the OMEGA signal were very different between the UW and the PASSCAL instruments. In both cases, as in any data which use the OMEGA signal as a time reference, there is always the possibility of errors in multiples of ten seconds which may still be present although all known cases have been corrected for. Aside from the aforementioned possibilities, the timing of the University of Wisconsin data may be regarded as reliable. As for the PASSCAL data, the quest for good timing was of great concern during this unexpectedly protracted post-processing phase. It was apparent early on that although there were two different types of reference clocks used in APT89, neither were immune from deficiencies in both hardware and software. Of course, this is a characteristic not uncommon in prototype equipment, but nonetheless ultimately led to uncertainties in the timing of these data. The bottom line for the PASSCAL data is beware. However, if one is still interested in using arrival times of these data, then please read Appendix B. If timing is not crucial, then avoid this appendix and the subdirectory "apt89/TIME".

2.4. Data Report Format

Included in the apt89/INFO directory is this document in UNIX troff format and the map in PostScript format. On a PostScript printer, the text in this document and the map can be printed using

```
tbl apt89.ms | psroff -ms
lpr apt89_map.ps
```

The ASCII versions of Table 1 and Table 3 are called "apt89.station" and "apt89.event" respectively.

3. Acknowledgements

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4. Data Distribution

The data referenced herein may be obtained through:

IRIS Data Management Center
8701 Mopac Blvd., Suite 205
Austin, TX 78759
(512) 471-0403,0404,0405

5. Appendix A - Site Descriptions

FLOR - PASSCAL station located on outcrop in the ESE-WNW trending Favourable Lake metavolcanic/metasedimentary belt of Archean age. Station is sited on mafic metavolcanics near the eastern shore of South Trout Lake, almost due north of abandoned camp of Favourable Lake. This station had serious flooding problems for much of the experiment and was finally moved to higher ground after 242:23:00. Station site accessible only by plane. [Favourable Lake - Berens Lake Geological Compilation Series, Map 2262, Kenora District, Ontario Geological Survey]

NSOW - Wisconsin station located on outcrop of Archean porphyritic granitic rocks, just west of North Spirit Lake metavolcanic/metasedimentary belt of Archean age. Station site accessible only by plane. [Geologic sheet, see FLOR]

NAOR - PASSCAL station located on Archean porphyritic granitic rock outcrop in wooded site near the terminus of the Nungesser Road, NNW of Red Lake, Ontario. Some problems with bears. [Geologic sheet, see FLOR]

NBOW - Wisconsin station located on outcrop of Archean granitic rocks. Early data plagued by telluric current injections. Also a popular wildlife attraction. In clearing of wooded area. [Geologic sheet, see FLOR]

RLOR and RLOW - Co-located PASSCAL (RLOR) and Wisconsin (RLOW) stations on the site of the Red Lake, Ontario RSTN station RSON. RLOW situated on nearby Archean granitic outcrop in an unsuccessful attempt to escape telluric currents. Both Kinemetrics and Guralp seismometers were run simultaneously for some of the time at RLOR. Both sensors were buried in sand within the RSON enclosure and set on brass spikes. Few trees due to fire several years back. [Red Lake - Birch Lake Sheet, Geological Compilation Series, Map 2175, Kenora District, Ontario Geological Survey]

EFOR - PASSCAL station with Guralp CMG-3 seismometers located on Archean granitic outcrop. In closely wooded area renowned for its aggressive mosquito population which survived well into late fall. Serious long period noise problems arose when the sawdust in which the Guralps were packed to reduce local air convection became soaked by water seepage from beneath. [Geological sheet, see RLOR]

CROW - Wisconsin station located on Archean granitic outcrop just east of a region of extensive paragneiss doming. Wooded. [Geological sheet, see RLOR]

DLOR - PASSCAL station located in wooded area on Archean granitic outcrop, part of Atikwa batholith in the Kenora Mining District. DLOR was the best station of the experiment. [Kenora - Fort Francis, Geological Compilation Series, Map 2443, Ontario Geological Survey]

CNOW - Wisconsin station located on Archean granitic outcrop, part of the Jackfish Lake - Weller Lake Pluton Complex in Kenora Mining District. Wooded [Geological sheet, see DLOR]

MAMW - Wisconsin station located on Archean metasedimentary outcrop in northern Minnesota. [International Falls Sheet, Geologic Map of Minnesota]

TRMW - Wisconsin station located on Pleistocene and Holocene sedimentary deposits, mostly unconsolidated, about 200 m thick overlying Archean granitic basement rocks. [Roseau Sheet, Geologic Map of Minnesota. Basement depth from Geologic Map of Minnesota, Bedrock Topography]

FVNR and FVNW - Co-located PASSCAL (FVNR) and Wisconsin (FVNW) stations sited in glacial sediment approximately 100 m thick overlying early Cretaceous marine sediments which are in turn underlain at a depth of about 600 m by Archean basement rock. Kinemetrics sensors set on brass spikes. Open area. [Depth to Bedrock in North Dakota, Misc. Map No. 26, North Dakota Geol. Survey; Bedrock Map of North Dakota, Misc. Map No. 21, North Dakota Geol. Survey; Geologic Highway Map of North Dakota, Misc. Map No. 29, North Dakota Geol. Survey]

SHNW - Wisconsin station located in glacial sediment approximately 15 m thick overlying Mesozoic/Paleozoic sedimentary rocks of the Williston Basin, approximately 1000 m thick. Sedimentary section underlain by Precambrian crystalline basement. Open area with few nearby trees. [Geologic sheets, see FVNR]

MCNW - Wisconsin station located in glacial sediment approximate 200 m thick. Underlain by Williston Basin Phanerozoic sedimentary section (Paleozoic through Tertiary) some 2500 m thick, which was laid down on crystalline Precambrian basement. Open area. [Geologic sheets, see FVNR]

STNR - PASSCAL station located in glacial sediment approximately 30 m thick overlying Williston Basin Phanerozoic sedimentary rocks some 2500 m thick laid down on Precambrian crystalline basement. Sensors set on brass spikes. Open area. [Geologic sheets, see FVNR]

HANW - Wisconsin station located in glacian soil approximately 15 m thick atop the Tertiary Sentinal Butte Formation. Williston Basin section about 3500 m thick in this area. Open area. [Geologic sheets, see FVNR]

LENR - PASSCAL station located in soil of the Tertiary Cannonball Formation of the Williston Basin sedimentary sequence. Basin about 3500 m thick in this area. Sensors set on concrete pad. Open area. [Geologic sheets, see FVNR]

LPSW - Wisconsin station located in soil of Williston Basin in South Dakota. Near axis of maximum Basin thickness, about 3500 m in this region. Treeless area.

OPSR - PASSCAL station located in soil of Williston Basin, South Dakota, NW of Black Hills Uplift. Sensors set on concrete pad. Treeless.

BFSW - Wisconsin station in soil overlying Cretaceous sedimentary marine deposits on NNW flank of Black Hills Uplift. Open area.

CPSW - Wisconsin station located on outcrop of Paleozoic sedimentary rocks, on SSW flank near core of the Black Hills Uplift. Structure striking NNE-SSW. Open area.

GLWW - Wisconsin station located in soil of early Tertiary deposits of the Powder River Basin, west of Black Hills Uplift and east of Bighorn Uplift. Powder River Basin, consisting of sedimentary rocks Paleozoic to Tertiary in age is estimated to be about 4000 m thick in this region. Basin overlies Precambrian crystalline rocks of the Bighorn Uplift. Open plains area. [Geologic information from: Geological Highway Map of Northern Rocky Mountain Region, compiled by AAPG]

DIWR - PASSCAL station located in soil of early Tertiary sedimentary deposits of Powder River Basin, SW of Black Hills Uplift and SW of Bighorn Uplift. Powder River Basin as described for GLWW, with thickness about 4000 m in region of DIWR. Sensors set on brass spikes. Open plains area. [Geologic information, see GLWW]

6. Appendix B - APT89 Timing Analysis

There are two sets of files which attempt to characterize the timing of the PASSCAL data.

(1) stnm.corr [2]

These two files are the result of cross-correlations of data which were recorded by the Wisconsin and PASSCAL instruments simultaneously at the two co-located stations. The two stations were at Fordville, ND and Red Lake, ONT and only operated during the early part of the experiment. Due to instrument specific glitches, some of the results may be dubious, but these have been appropriately flagged. The PASSCAL data were not time-corrected based on these results.

(2) stnm.time [10]

These ten files summarize the timing analysis of the PASSCAL event data. Each line may contain at most five columns:

(a) the filename of the extracted event

(b) whether the clock claimed to be locked (Y | N)

(c) whether the time appeared to be ok (OK | N)

(d) whether the time was repaired (Y | N)

(e) whether the time still contains errors (OK | *value* | U)

Later, I will briefly discuss how these claims dare be made, but in general, the last column is the most relevant. If it says "OK", then based on the available information, the time for that file can be regarded as good. If the last column contains a *value*, then there remains an error which cannot be removed without re-interpolating to a new sampling rate or without some additional clairvoyance. If the last column contains a "U", then there is almost certainly a time error remaining, but I have not a clue as to its size. In cases where this "unknown" error is clearly present, but not known precisely, I have left it untouched, so that such *ad hoc* corrections would not lead to an unfounded trust in the timing.

If it were not for the co-location experiments, this appendix would not exist. Upon careful inspection of the data collected at these sites, it soon became clear that there were serious differences between the timing of the two seismographs. Fortunately, the UW instrument had recorded the Omega time signal in addition to the seismic channels, so it could be shown unequivocally that the PASSCAL instrument was the one with the incorrect time. Because only three percent of the extracted PASSCAL event data had corresponding University of Wisconsin data, the main question then was what to do about the other 97 percent. In the absence of the actual GOES and OMEGA time signals, the only recourse was to inspect the data for internal inconsistencies and repair them if possible.

The way to check for internal inconsistency is very straightforward. For each block of data, we are given the time stamp of the first data point, the nominal sample rate and the number of samples before the next time stamp. With these three values, we can predict what the following time stamp should be. If the "predicted" time differs from the "actual" time of the next block, then the data are not internally consistent (i.e. one of the time stamps must be wrong). The way we hope to resolve this quandary is to rely on the State-of-Health log which indicates when the internal clock of the instrument has locked to the external time signal. We would expect only to find such an inconsistency (or time tear) if there was a extended period when the external signal was not being received well. During this time, the internal clock would not be ticking at the same rate as the external clock, and they would slowly drift away from each other. When the signal was once again received, the internal clock would be reset (or slewed) to the correct time and an error between successive time stamps would be seen in the "continuous" data. Assuming a linear drift rate of the internal clock while unlocked, the "actual" time can be reconstructed. In this way, an apparent inconsistency can be resolved and repaired. (While a drifting clock implies a change in the sampling rate from the nominal, there were no repairs made to the sampling rates of the extracted events. Therefore, there may be an accumulated error over the 20 minute time window. This remaining error will appear in the fifth column of the "stnm.time" files.)

Of course, not all inconsistencies adhered to this simple scenario. There were many instances where a time tear would occur and then self-heal itself some time later. These were relatively easy to spot because they almost always appeared with values of 0.5, 1.0, or 2.0 seconds and never showed any correlation with changes in clock status. Although mysterious, they displayed a predictable pattern and could therefore be repaired. Another source of time tears occurred when there were rapid changes in the clock lock status. Usually, the errors were tens of milliseconds, but sometimes became as large as hundreds of milliseconds. In any event, it is unclear which "side" of the time tear represents reliable time, so a repair could not be justified. (Most of the *values* listed in the fifth column of the "stnm.time" files result from such instances.)

By far the scariest are time tears which occurred while the clock was locked. Obviously, one expects a locked clock to represent reliable time, so is it possible to unsnarl the inconsistency? Did the clock lose lock, but simply decide not to tell us? Or did the internal clock never really phase lock to the external signal in the first place? Or was it something else which had not occurred to me during one of my recurring nightmares? One might have suggested that on account of such behavior, the way in which the PASSCAL dataloggers handled time should not be trusted at all. Because this is decidedly defeatist and pessimistic, I did not ascribe to it strictly. In spite of this error in judgement and the ensuing months spent trying to making sense of these time tears and incorporating appropriate time corrections, there will still be timing errors in these data.

In conclusion, the outcome of this timing analysis could not correct the data set completely. Undoubtedly, this is not possible based on the amount of information present. Rather, the most to be expected is that internal consistency has been checked and repaired when possible. Without the actual time signal accompanying the waveforms as has been traditionally done, one can never be absolutely certain of the true time of these data. These are the prices we pay in prototype experiments, but with the continuing explosion of seismological data, it is clear that this "on the fly" approach to timing will ultimately be the most efficient. It is hoped that the trying lessons learned during these debugging days will continue to improve the quality of the data in experiments to come.

TABLE 1 -- Station Locations and Seismometer Orientations

Station	Location	Lat.	Lon.	Elev. (m)	Magnetic Declination (E of true N)	Channel	Inclination from vertical	Azimuth (E of true N)
flor	FAVOURABLE LAKE, ONT	52.87	-93.65	290	1.9	(1) vert	0	
						(2) north	90	355.9
						(3) east	90	82.9
nsow	NORTH SPIRIT, ONT	52.46	-93.05	330	1.2	(1) vert	0	
						(2) north	90	356.2
						(3) east	90	87.2
naor	NUNGESSERA, ONT	51.72	-93.67	340	2.2	(1) vert	0	
						(2) north	90	354.2
						(3) east	90	84.2
nbow	NUNGESSERB, ONT	51.41	-93.69	412	2.2	(1) vert	0	
						(2) north	90	356.2
						(3) east	90	81.2
rlor	RED LAKE, ONT (at rson)	50.85	-93.70	221	2.3	(1) vert	0	
						(2) north	90	356.3
						(3) east	90	86.3
						(4) vert	180	
						(5) north	90	356.3
						(6) east	90	86.3
rlow	RED LAKE, ONT (at rson)	50.85	-93.70	221	2.3	(1) vert	0	
						(2) north	90	356.3
						(3) east	90	86.3
efor	EAR FALLS, ONT	50.53	-93.30	370	2.0	(1) vert	180	
						(2) north	90	358.0
						(3) east	90	88.0
crow	CAMP ROBINSON, ONT	50.15	-93.07	390	1.9	(1) vert	0	
						(2) north	90	355.9
						(3) east	90	85.9
dlor	DORE LAKE, ONT	49.61	-92.86	392	1.7	(1) vert	0	
						(2) north	90	352.7
						(3) east	90	82.7
cnow	CEDAR NARROWS, ONT	49.07	-93.14	420	2.1	(1) vert	0	
						(2) north	90	350.1
						(3) east	90	80.1
mamw	MARGIE, MN	48.13	-93.94	373	3.2	(1) vert	0	
						(2) north	90	353.2
						(3) east	90	86.2
trmw	THIEF RIVER FALLS, MN	48.11	-96.43	312	5.7	(1) vert	0	
						(2) north	90	358.7
						(3) east	90	88.7
fvnr	FORDVILLE, ND	48.23	-97.74	360	6.9	(1) vert	0	
	before 166:00:50					(2) north	90	6.9
						(3) east	90	96.9
	after 166:00:50					(2) north	90	356.9
						(3) east	90	89.9
fvnw	FORDVILLE, ND	48.23	-97.74	360	6.9	(1) vert	0	
						(2) north	90	11.9
						(3) east	90	96.9
shnw	SHEYENE, ND	47.85	-99.23	454	8.3	(1) vert	0	
						(2) north	90	357.3
						(3) east	90	83.3

mcnw	MCCLUSKY, ND	47.55	-100.36	622	9.2	(1) vert	0	
						(2) north	90	359.2
						(3) east	90	89.2
stnr	STEELE, ND	46.67	-99.88	585	8.7	(1) vert	0	
	before 241:19:18					(2) north	90	359.2
						(3) east	90	89.2
	after 241:19:18					(2) north	90	2.7
						(3) east	90	96.7
hanw	HANOVER, ND	47.18	-101.55	658	10.1	(1) vert	0	
						(2) north	90	0.1
						(3) east	90	86.1
lenr	LEITH, ND	46.19	-101.59	652	10.0	(1) vert	0	
						(2) north	90	16.0
						(3) east	90	103.0
lpsw	LODGEPOLE, SD	45.80	-102.61	829	10.7	(1) vert	0	
						(2) north	90	347.7
						(3) east	90	77.7
opsr	OPAL, SD	44.91	-102.51	811	10.5	(1) vert	0	
						(2) north	90	1.5
						(3) east	90	91.5
bfsw	BELLE FOURCHE, SD	45.02	-103.97	978	11.5	(1) vert	0	
						(2) north	90	0.5
						(3) east	90	86.5
cpsw	CUSTER PARK, SD	43.71	-103.39	1402	10.9	(1) vert	0	
						(2) north	90	357.9
						(3) east	90	87.9
glww	GILLETTE, WY	44.19	-105.68	1497	12.4	(1) vert	0	
						(2) north	90	0.4
						(3) east	90	93.4
diwr	DILTS' RANCH, WY	43.46	-105.58	1469	12.1	(1) vert	0	
						(2) north	90	356.1
						(3) east	90	88.1

TABLE 2 -- Reference Clocks Used by PASSCAL Stations

Station	Clock	When
flor	GOES OMEGA	before 254:21:00 after 254:21:00
naor	OMEGA	always
rlor	GOES OMEGA	before 184:01:30 after 184:01:30
efor	OMEGA	always
dlor	GOES	always
fvnr	GOES	always
stnr	GOES	always
lenr	OMEGA GOES	before 196:21:50 after 196:21:50
opsr	OMEGA	always
diwr	OMEGA	always

TABLE 3 -- Event Locations

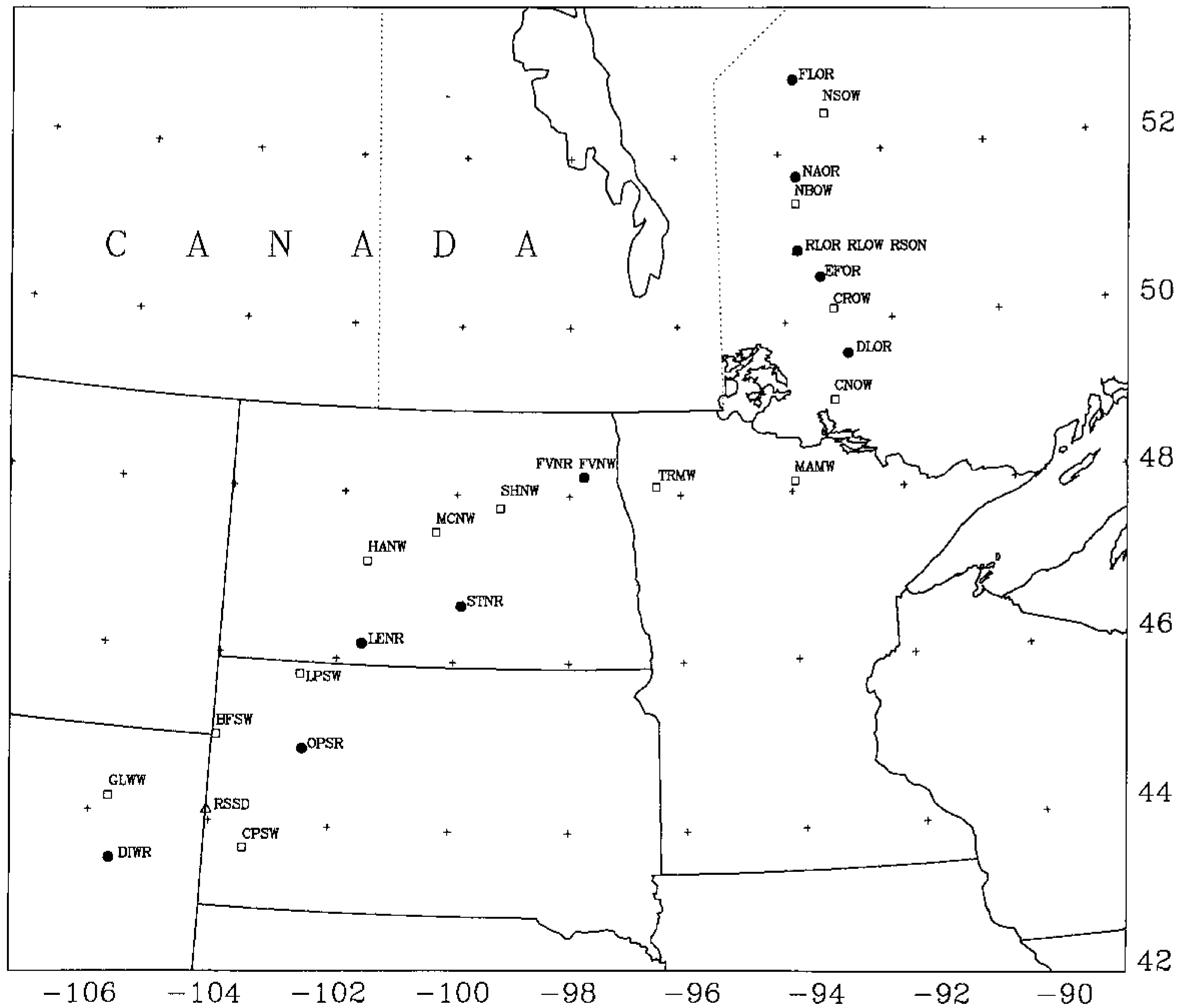
Origin Time	Latitude	Longitude	Depth (km)	mb	Ms	Region
1989 159 09 51 56.8	-19.531	-173.736	22.0	5.5	5.4	TONGA ISLANDS
1989 160 12 19 35.7	71.432	-4.371	10.0	5.6	5.4	JAN MAYEN ISLAND REGION
1989 160 15 34 11.6	-7.865	117.517	245.0	5.8	0.0	BALI SEA
1989 160 16 52 12.1	20.260	145.147	148.0	5.4	0.0	MARIANA ISLANDS
1989 160 18 04 05.7	39.671	74.490	33.0	5.2	4.7	SOUTHERN XINJIANG, CHINA
1989 161 17 29 58.2	-22.252	-138.734	0.0	5.5	0.0	TUAMOTO ARCHIPELAGO REGION
1989 162 12 21 49.7	-51.752	158.855	10.0	5.2	5.1	NORTH OF MACQUARIE ISLAND
1989 162 13 24 32.1	35.107	-35.008	9.0	5.8	5.5	NORTH ATLANTIC RIDGE
1989 163 00 04 09.8	21.861	89.763	5.0	6.1	5.1	BANGLADESH
1989 163 05 47 35.8	-15.283	167.572	247.0	5.4	0.0	VANUATU ISLANDS
1989 163 13 11 51.6	-30.169	-178.918	82.0	5.6	0.0	KERMADEC ISLANDS
1989 163 18 21 03.3	-22.554	-175.826	70.0	5.5	0.0	TONGA ISLANDS REGION
1989 164 17 49 40.6	-3.670	140.139	71.0	5.4	0.0	WEST IRIAN
1989 165 00 29 00.0	51.488	-174.300	33.0	5.2	4.5	ANDREANOF IS., ALEUTIAN IS.
1989 165 00 35 58.3	51.547	-174.316	33.0	5.3	4.9	ANDREANOF IS., ALEUTIAN IS.
1989 165 10 17 35.2	12.875	143.351	126.0	5.5	0.0	SOUTH OF MARIANA IS.
1989 165 18 06 38.3	34.289	26.055	13.0	5.2	5.1	CRETE
1989 165 21 44 35.2	40.085	144.609	33.0	5.3	4.6	OFF E. COAST OF HONSHU, JAPAN
1989 167 07 18 35.5	13.224	145.154	67.0	5.5	0.0	TAJIK, SSR
1989 167 10 51 21.6	57.755	-153.992	58.0	5.8	0.0	MARIANA ISLANDS
1989 167 22 39 20.5	-47.448	100.080	10.0	5.3	0.0	SOUTHEAST INDIAN RISE
1989 167 22 51 08.9	-47.492	100.156	10.0	5.4	5.4	SOUTHEAST INDIAN RISE
1989 167 23 42 35.1	31.807	137.982	359.0	5.9	0.0	SOUTH OF HONSHU, JAPAN
1989 168 00 13 25.6	-2.902	143.462	33.0	5.3	4.7	PAPUA NEW GUINEA REGION
1989 168 14 57 48.4	-31.419	-67.550	27.0	5.3	4.5	SAN JUAN PROVINCE, ARGENTINA
1989 168 18 28 08.6	-40.494	-74.674	33.0	5.6	5.0	OFF COAST OF SOUTHERN CHILE
1989 169 14 06 28.8	17.761	-68.811	62.0	5.9	0.0	MONA PASSAGE
1989 170 16 00 47.9	-22.113	-67.559	188.0	5.5	0.0	CHILE-BOLIVIA REGION
1989 170 20 16 10.5	-55.672	-28.247	33.0	5.6	5.1	SOUTH SANDWICH IS. REGION
1989 171 05 41 43.5	52.334	174.184	48.0	5.2	4.3	NEAR IS., ALEUTIAN REGION
1989 171 18 07 43.6	52.527	172.508	33.0	5.2	4.6	NEAR IS., ALEUTIAN REGION
1989 171 23 40 38.9	-3.867	86.993	10.0	5.2	4.6	SOUTH INDIAN OCEAN
1989 172 08 58 18.4	-52.362	160.350	10.0	5.2	4.7	MACQUARIE ISLANDS REGION
1989 172 23 51 02.0	-21.785	-176.493	182.0	5.6	0.0	FIJI ISLANDS REGION
1989 173 11 06 06.8	28.252	130.644	33.0	5.3	0.0	RYUKYU ISLANDS
1989 173 21 15 00.8	37.283	-116.412	0.0	5.3	4.8	SOUTHERN NEVADA
1989 174 12 00 53.3	22.311	142.996	170.0	5.3	0.0	VOLCANO ISLANDS REGION
1989 174 16 37 56.8	-57.925	-25.382	33.0	5.3	0.0	SOUTH SANDWICH IS. REGION
1989 175 12 58 39.1	-28.336	-66.312	21.0	5.4	5.2	CATAMARCA PROVINCE, ARGENTINA
1989 175 15 02 07.7	1.974	-79.066	25.0	5.3	4.6	NEAR COAST OF ECUADOR
1989 176 11 15 59.4	32.912	-39.609	10.0	5.2	4.6	NORTH ATLANTIC RIDGE
1989 176 12 30 05.9	-6.113	149.062	72.0	5.2	0.0	NEW BRITAIN REGION
1989 176 20 37 32.5	1.134	-79.616	15.0	5.9	6.1	NEAR COAST OF ECUADOR
1989 177 03 27 04.0	19.362	-155.083	9.0	5.8	6.1	HAWAII
1989 177 10 38 39.5	39.112	-28.242	11.0	5.7	5.7	AZORES
1989 178 07 10 22.6	51.568	-174.339	33.0	5.2	5.0	ANDREANOF ISLANDS
1989 178 15 30 00.0	37.275	-116.354	0.0	4.9	0.0	SOUTHERN NEVADA
1989 178 17 43 09.0	-63.723	-156.105	10.0	5.4	5.5	SOUTH PACIFIC CORDILLERA
1989 179 03 00 28.9	45.096	151.292	44.0	5.6	5.1	KURIL ISLANDS
1989 179 21 24 12.4	-57.788	-147.449	10.0	5.5	5.7	SOUTH PACIFIC CORDILLERA
1989 179 22 11 58.9	-6.223	148.814	50.0	5.4	0.0	NEW BRITAIN REGION
1989 179 23 44 51.4	-7.604	127.342	173.0	5.3	0.0	BANDA SEA
1989 180 00 18 39.8	-22.960	-175.319	34.0	5.2	5.1	TONGA ISLANDS REGION
1989 180 03 57 33.1	-6.289	154.817	81.0	5.3	0.0	SOLOMON ISLANDS
1989 180 05 25 51.5	-4.497	102.018	42.0	5.3	5.0	SOUTHERN SUMATERA
1989 182 03 59 14.4	-6.447	147.861	44.0	5.3	5.0	EAST PAPUA NEW GUINEA REGION
1989 184 17 09 55.8	51.617	-175.208	33.0	5.7	5.7	ANDREANOF IS., ALEUTIAN, IS.
1989 187 17 25 29.4	-16.632	-177.365	22.0	5.3	5.5	FIJI ISLANDS REGION
1989 187 20 22 53.2	8.014	126.786	60.0	5.3	4.5	MINDANAO, PHILIPPINE ISLANDS
1989 188 12 27 51.1	-36.265	-99.250	10.0	5.2	5.0	SOUTHERN PACIFIC OCEAN
1989 188 19 41 18.8	-4.823	128.973	34.0	5.5	4.8	BANDA SEA
1989 188 21 45 37.5	-3.370	135.628	33.0	5.0	4.1	WEST IRIAN REGION
1989 188 23 29 37.2	-13.592	166.586	95.0	5.1	0.0	VANUATU ISLANDS
1989 189 00 48 09.8	-17.720	-172.945	40.0	5.1	5.0	TONGA ISLANDS REGION
1989 189 03 46 57.6	49.888	78.802	0.0	5.6	4.1	EASTERN KAZAKH SSR
1989 189 09 31 57.1	52.841	159.859	30.0	5.5	4.2	OFF E. COAST OF KAMCHATKA
1989 189 10 33 07.9	1.162	121.476	41.0	5.5	5.1	MINAHASSA PENINSULA

1989 189 10 56 54.2	52.654	-164.053	33.0	5.1	5.0	FOX ISLANDS, ALEUTIAN ISLANDS
1989 190 09 46 39.6	-1.577	-15.548	10.0	5.4	5.4	NORTH OF ASCENSION ISLAND
1989 190 17 46 27.1	-57.078	-23.965	33.0	5.2	4.7	SOUTH SANDWICH ISLANDS REGION
1989 191 23 59 15.1	46.050	151.316	75.0	5.5	0.0	KURIL ISLANDS
1989 193 17 36 49.7	-7.786	122.902	259.0	5.2	0.0	FLORES SEA
1989 194 02 02 23.0	-13.259	167.110	201.0	5.3	0.0	VANUATU ISLANDS
1989 195 15 43 18.1	-1.472	-15.546	10.0	5.4	5.3	NORTH OF ASCENSION ISLAND
1989 195 20 42 40.1	-8.081	125.129	9.0	6.4	6.2	TIMOR
1989 196 00 09 16.1	22.809	94.560	107.0	5.4	0.0	BURMA
1989 197 22 10 54.5	-30.389	-178.616	115.0	5.2	0.0	KERMADEC ISLANDS
1989 199 10 41 14.6	53.384	160.376	33.0	5.4	4.8	NEAR E. COAST OF KAMCHATKA
1989 199 23 52 39.5	-17.569	168.683	41.0	5.2	0.0	VANUATU ISLANDS
1989 200 03 14 09.4	-7.338	154.331	46.0	5.2	4.3	SOLOMON ISLANDS
1989 201 04 41 59.2	4.433	126.671	63.0	5.4	0.0	TALAUD ISLANDS
1989 201 04 53 20.6	2.845	99.127	187.0	5.2	0.0	NORTHERN SUMATERA
1989 201 06 27 25.1	5.048	95.635	82.0	5.9	0.0	NORTHERN SUMATERA
1989 201 12 09 53.3	-18.870	-175.528	240.0	5.4	0.0	TONGA ISLANDS
1989 202 03 09 16.4	30.029	99.455	35.0	5.5	5.3	SICHUAN PROVINCE, CHINA
1989 203 05 02 11.5	2.299	128.142	141.0	6.4	0.0	HALMAHERA
1989 203 12 52 50.4	-54.412	-132.680	10.0	5.3	5.6	SOUTH PACIFIC CORDILLERA
1989 205 03 27 48.8	36.085	71.069	95.0	5.8	0.0	AFGHANISTAN-USSR BORDER
1989 205 10 03 45.8	-18.874	176.789	31.0	5.6	5.4	FIJI ISLANDS REGION
1989 205 10 11 24.2	-18.823	176.674	33.0	5.3	5.5	FIJI ISLANDS REGION
1989 205 10 53 10.6	-18.880	176.811	19.0	5.5	5.4	FIJI ISLANDS REGION
1989 206 21 39 36.3	4.507	126.028	185.0	5.1	0.0	TALAUD ISLANDS
1989 206 21 54 23.1	-7.191	122.715	620.0	5.6	0.0	FLORES SEA
1989 206 22 16 12.8	-32.099	-178.134	33.0	5.3	4.9	SOUTH OF KERMADEC ISLANDS
1989 207 12 26 11.2	33.713	141.312	60.0	5.2	0.0	OFF E. COAST OF HONSHU, JAPAN
1989 210 16 57 05.3	-4.441	144.027	105.0	5.4	0.0	NORTH OF PAPUA, NEW GUINEA
1989 211 04 38 24.5	33.236	140.764	61.0	5.3	0.0	SOUTH OF HONSHU, JAPAN
1989 211 09 29 16.0	-52.602	12.927	10.0	5.6	5.7	SOUTHWEST OF AFRICA
1989 211 19 14 37.3	4.695	95.907	22.0	5.2	4.8	NORTHERN SUMATERA
1989 211 19 36 18.2	-5.006	130.943	56.0	5.3	4.9	BANDA SEA
1989 212 17 07 27.9	-8.048	121.384	13.0	6.3	6.2	FLORES ISLAND REGION
1989 213 00 18 04.9	-4.511	139.022	14.0	6.0	5.8	WEST IRIAN
1989 213 05 24 51.8	-11.618	164.686	33.0	5.6	5.3	SANTA CRUZ ISLANDS REGION
1989 213 12 44 02.9	-31.464	-177.525	103.0	5.4	0.0	KERMADEC ISLANDS REGION
1989 213 15 03 53.4	-21.952	170.568	60.0	5.3	0.0	LOYALTY ISLANDS REGION
1989 213 23 27 52.4	-3.660	150.695	10.0	5.2	5.5	NEW IRELAND REGION
1989 214 03 37 28.1	-2.686	127.312	29.0	5.6	5.0	CERAM SEA
1989 214 10 24 21.3	2.774	96.143	28.0	5.1	4.9	NORTHERN SUMATERA
1989 215 02 24 20.5	1.009	126.100	65.0	5.3	0.0	MOLUCCA PASSAGE
1989 215 04 09 48.1	32.456	137.346	418.0	5.2	0.0	SOUTH OF HONSHU, JAPAN
1989 215 11 07 18.0	-59.994	-26.680	33.0	5.7	5.7	SOUTH SANDWICH ISLANDS REGION
1989 215 11 31 20.4	23.043	121.965	10.0	5.9	6.4	TAIWAN
1989 215 14 56 27.3	-25.087	87.755	10.0	5.1	0.0	SOUTH INDIAN OCEAN
1989 215 19 21 41.6	33.578	141.213	48.0	5.0	0.0	OFF E. COAST OF HONSHU, JAPAN
1989 215 22 25 55.5	-22.531	179.129	592.0	5.5	0.0	SOUTH OF FIJI ISLANDS
1989 217 06 55 51.0	76.118	134.578	10.0	5.3	5.0	LAPTEV SEA
1989 217 23 30 31.9	33.221	140.794	55.0	5.2	0.0	SOUTH OF HONSHU, JAPAN
1989 218 06 36 29.2	1.883	128.251	113.0	5.7	0.0	HALMAHERA
1989 218 07 43 39.2	1.093	126.307	50.0	5.3	5.0	MOLUCCA PASSAGE
1989 218 08 19 56.1	-23.157	-68.321	114.0	5.3	0.0	NORTHERN CHILE
1989 218 13 17 43.4	59.939	-140.475	10.0	5.3	5.2	SOUTHERN ALASKA
1989 218 22 53 56.5	42.797	145.117	44.0	5.7	5.1	HOKKAIDO, JAPAN REGION
1989 219 14 49 28.4	-5.417	152.022	36.0	5.1	5.0	NEW BRITAIN REGION
1989 219 14 56 30.7	-5.594	151.993	33.0	5.2	0.0	NEW BRITAIN REGION
1989 220 07 59 06.2	-40.121	174.330	121.0	5.5	0.0	COOK STRAIT, NEW ZEALAND
1989 220 08 13 27.5	37.130	-121.952	15.0	4.9	4.5	CENTRAL CALIFORNIA
1989 220 23 44 04.4	-22.723	-68.478	102.0	5.3	0.0	NORTHERN CHILE
1989 221 00 40 36.2	-20.644	-173.617	37.0	5.3	5.0	TONGA ISLANDS
1989 221 16 01 25.4	24.559	94.707	85.0	5.2	0.0	BURMA-INDIA BORDER REGION
1989 222 01 55 57.2	5.898	124.424	55.0	5.4	5.7	MINDANAO, PHILIPPINE ISLANDS
1989 222 08 23 45.0	5.875	124.431	42.0	5.0	4.7	MINDANAO, PHILIPPINE ISLANDS
1989 222 10 44 36.8	-61.895	154.623	10.0	5.2	5.6	BALLENY ISLANDS REGION
1989 222 11 46 28.8	5.977	124.379	44.0	5.4	5.2	MINDANAO, PHILIPPINE ISLANDS
1989 222 19 25 20.7	-19.036	176.707	33.0	5.2	4.4	SOUTH OF FIJI ISLANDS
1989 223 04 21 23.5	45.833	150.690	84.0	5.2	0.0	KURIL ISLANDS
1989 223 06 55 54.4	-18.916	176.883	33.0	5.2	0.0	FIJI ISLANDS REGION
1989 223 20 58 42.4	-7.237	122.689	632.0	5.4	0.0	FLORES SEA
1989 224 00 40 10.7	0.800	126.817	51.0	5.7	0.0	MOLUCCA PASSAGE
1989 224 15 31 49.2	18.288	-100.974	68.0	5.3	0.0	GUERRERO, MEXICO

1989 224 16 46 43.3	8.682	125.718	55.0	5.9	0.0	MINDANAO, PHILIPPINE ISLANDS
1989 224 20 46 40.7	-20.502	-173.929	37.0	5.3	5.3	TONGA ISLANDS
1989 226 17 51 08.8	-19.016	176.652	33.0	5.8	5.9	SOUTH OF FIJI ISLANDS
1989 226 18 12 40.7	-19.010	176.662	33.0	5.4	0.0	SOUTH OF FIJI ISLANDS
1989 226 18 15 53.8	-18.957	176.674	33.0	5.5	0.0	FIJI ISLANDS REGION
1989 226 19 02 33.4	-19.032	176.862	33.0	5.3	0.0	SOUTH OF FIJI ISLANDS
1989 227 10 04 22.3	-38.307	-93.822	10.0	5.4	5.3	WEST CHILE RISE
1989 229 11 03 10.6	-17.701	167.187	10.0	5.2	4.8	VANUATU ISLANDS
1989 229 15 01 22.3	-4.371	153.002	108.0	5.3	0.0	NEW IRELAND REGION
1989 230 03 46 26.0	-55.053	-27.846	33.0	5.6	5.5	SOUTH SANDWICH ISLANDS REGION
1989 231 13 19 20.3	-6.507	130.028	164.0	5.7	0.0	BANDA SEA
1989 232 09 10 15.9	9.255	123.697	53.0	5.3	4.1	NEGROS, PHILIPPINE ISLANDS
1989 232 11 16 56.5	11.766	41.942	11.0	5.8	6.3	ETHIOPIA
1989 232 11 17 55.2	11.919	41.963	10.0	5.6	0.0	ETHIOPIA
1989 232 11 46 28.1	11.884	41.812	10.0	6.1	5.6	ETHIOPIA
1989 232 11 56 17.8	11.764	41.964	10.0	5.3	0.0	ETHIOPIA
1989 232 13 25 26.0	11.898	41.884	10.0	5.2	0.0	ETHIOPIA
1989 232 13 26 19.4	11.880	41.880	10.0	5.3	6.1	ETHIOPIA
1989 232 18 32 29.9	37.278	21.203	10.0	5.4	5.6	SOUTHERN GREECE
1989 232 18 39 48.9	11.985	41.870	10.0	5.4	0.0	ETHIOPIA
1989 232 18 54 05.3	11.896	41.764	10.0	5.2	0.0	ETHIOPIA
1989 232 19 25 56.5	11.904	41.824	11.0	6.2	5.7	ETHIOPIA
1989 233 01 09 06.6	11.874	41.870	15.0	6.3	6.2	ETHIOPIA
1989 233 05 03 05.6	11.942	41.769	9.0	5.8	5.7	ETHIOPIA
1989 233 05 05 45.4	11.821	41.732	10.0	5.3	0.0	ETHIOPIA
1989 233 18 25 41.0	-4.104	154.459	493.0	5.8	0.0	SOLOMON ISLANDS
1989 233 18 35 38.0	-4.143	154.782	541.0	5.1	0.0	SOLOMON ISLANDS
1989 233 23 12 41.4	24.094	122.478	42.0	5.6	6.3	TAIWAN REGION
1989 234 06 27 02.7	-5.030	151.386	132.0	5.2	0.0	NEW BRITAIN REGION
1989 234 07 56 09.6	41.463	142.066	65.0	5.3	0.0	HOKKAIDO, JAPAN REGION
1989 235 06 28 09.4	27.374	129.763	8.0	5.4	0.0	RYUKYU ISLANDS
1989 235 07 11 46.3	27.481	129.824	28.0	5.3	4.7	RYUKYU ISLANDS
1989 235 20 25 22.4	52.350	-168.025	33.0	5.3	4.7	FOX ISLANDS, ALEUTIAN ISLANDS
1989 236 18 55 21.2	41.687	49.273	33.0	5.2	0.0	CASPIAN SEA
1989 238 00 11 43.2	36.210	140.919	52.0	5.4	4.7	NEAR COAST OF HONSHU, JAPAN
1989 241 04 16 23.0	18.039	-105.667	21.0	5.7	6.6	OFF COAST OF JALISCO, MEXICO
1989 241 16 12 39.4	32.986	141.286	53.0	5.3	4.0	SOUTH OF HONSHU, JAPAN
1989 242 03 06 55.1	54.597	162.793	31.0	5.5	5.2	NEAR EAST COAST OF KAMCHATKA
1989 242 11 38 12.8	55.609	161.358	73.0	5.8	0.0	NEAR EAST COAST OF KAMCHATKA
1989 242 16 25 29.8	5.625	127.186	92.0	5.1	0.0	PHILIPPINE ISLANDS REGION
1989 243 08 17 22.5	-41.850	-71.678	154.0	5.4	0.0	S. CHILE-ARGENTINA BORDER
1989 243 11 04 58.7	-0.174	-17.801	10.0	5.4	4.7	NORTH OF ASCENSION ISLAND
1989 244 11 57 22.5	-6.699	108.426	221.0	5.3	0.0	JAVA
1989 245 04 16 57.3	50.039	79.019	0.0	5.0	0.0	EASTERN KAZAKH, SSR
1989 245 14 20 59.0	-17.819	-178.549	613.0	5.3	0.0	FIJI ISLANDS REGION
1989 245 16 53 26.7	-4.242	152.942	44.0	5.4	5.3	NEW BRITAIN REGION
1989 245 16 56 37.3	-4.227	153.163	33.0	5.2	0.0	NEW IRELAND REGION
1989 246 00 19 37.8	25.540	125.263	37.0	5.1	5.1	SOUTHWESTERN RYUKYU ISLANDS
1989 246 08 36 32.3	-4.527	139.084	10.0	5.1	4.6	WEST IRIAN
1989 246 20 52 15.5	-37.953	177.820	59.0	5.2	0.0	OFF E. COAST OF N. IS., N.Z.
1989 247 05 20 55.9	-4.219	136.667	9.0	5.8	6.0	WEST IRIAN REGION
1989 247 07 18 32.8	-33.329	-178.805	33.0	5.3	0.0	SOUTH OF KERMADEC ISLANDS
1989 247 13 14 58.3	55.543	-156.835	11.0	6.5	6.9	SOUTH OF ALASKA
1989 247 14 57 28.1	-33.262	-178.689	41.0	5.4	0.0	SOUTH OF KERMADEC ISLANDS
1989 248 05 51 55.2	4.260	127.408	42.0	5.6	5.0	TALAUD ISLANDS
1989 248 06 28 11.8	14.218	-93.755	35.0	5.6	4.9	NEAR COAST OF CHIAPAS, MEXICO
1989 248 11 25 55.8	29.459	128.560	18.0	5.2	5.3	EAST CHINA SEA
1989 248 19 49 03.8	-52.810	140.316	10.0	5.3	5.4	WEST OF MACQUARIE ISLAND
1989 249 14 45 51.0	0.976	126.106	36.0	5.8	5.5	MOLUCCA PASSAGE
1989 250 13 32 00.1	-30.197	-177.960	33.0	5.7	5.4	KERMADEC ISLANDS
1989 251 06 15 05.6	-52.766	9.851	10.0	5.3	5.6	SOUTHWEST OF AFRICA
1989 251 08 25 39.8	-30.178	-177.844	46.0	5.3	5.2	KERMADEC ISLANDS
1989 252 01 40 35.8	2.435	-79.761	6.0	6.0	5.0	SOUTH OF PANAMA
1989 252 10 38 06.9	51.310	-175.805	33.0	5.3	5.2	ANDREANOF ISLANDS
1989 255 15 29 15.5	-9.011	110.521	48.0	5.1	5.1	SOUTH OF JAVA
1989 256 03 31 35.9	-19.009	-174.921	122.0	5.6	0.0	TONGA ISLANDS
1989 256 11 40 46.0	-35.577	-17.063	11.0	5.6	6.2	SOUTH ATLANTIC RIDGE
1989 257 04 42 39.8	-26.141	-70.746	33.0	5.3	5.2	NEAR COAST OF NORTHERN CHILE
1989 257 19 10 25.7	1.644	127.322	103.0	6.0	0.0	HALMAHERA
1989 258 08 49 55.5	-19.329	-175.800	144.0	5.5	0.0	TONGA ISLANDS
1989 258 09 48 09.2	51.574	-173.367	33.0	5.4	5.1	ANDREANOF ISLANDS
1989 258 15 36 37.0	9.988	126.520	33.0	5.1	4.4	MINDANAO, PHILIPPINE ISLANDS

1989 258 16 40 25.0	-3.062	134.686	33.0	5.5	5.0	WEST IRIAN REGION
1989 258 18 34 13.0	53.232	159.719	51.0	5.6	0.0	NEAR EAST COAST OF KAMCHATKA
1989 259 01 49 15.9	-0.592	-77.469	10.0	5.4	0.0	ECUADOR
1989 259 02 05 08.9	40.337	51.534	54.0	6.4	6.5	CASPIAN SEA
1989 259 04 03 03.2	-32.561	-14.251	10.0	5.7	5.8	SOUTH ATLANTIC RIDGE
1989 259 07 27 11.3	2.121	125.301	33.0	5.1	5.0	TALAUD ISLANDS
1989 259 23 20 53.2	16.497	-93.671	108.0	6.0	0.0	CHIAPAS, MEXICO
1989 260 00 53 39.8	40.203	51.749	51.0	6.1	6.1	CASPIAN SEA
1989 260 05 48 01.9	-61.435	153.988	10.0	5.5	5.9	BALLENY ISLANDS REGION
1989 261 21 16 28.2	66.779	-136.028	23.0	5.1	4.8	NORTHERN YUKON TERRITORY
1989 262 16 47 34.7	-5.527	153.620	54.0	5.4	0.0	NEW IRELAND REGION
1989 263 13 19 32.0	51.184	178.821	33.0	5.5	5.8	RAT ISLANDS, ALEUTIAN ISLANDS
1989 264 16 46 35.0	-10.164	161.061	120.0	5.2	0.0	SOLOMON ISLANDS
1989 265 02 25 50.9	31.583	102.433	14.0	6.1	6.1	SICHUAN PROVINCE, CHINA
1989 266 17 51 38.2	22.621	121.971	31.0	5.5	5.1	TAIWAN REGION
1989 266 22 37 46.8	32.993	140.705	73.0	5.0	0.0	SOUTH OF HONSHU, JAPAN
1989 267 10 53 54.3	9.977	-59.851	47.0	5.1	4.5	NORTH ATLANTIC OCEAN
1989 267 10 55 20.9	20.697	94.968	134.0	5.3	0.0	BURMA
1989 267 22 09 49.2	-25.370	178.380	570.0	5.0	0.0	SOUTH OF FIJI ISLANDS
1989 268 14 17 47.1	-20.355	169.277	33.0	6.1	6.3	VANUATU ISLANDS
1989 268 18 47 18.0	-35.063	178.861	190.0	5.3	0.0	OFF E. COAST OF N. IS., N.Z.
1989 269 02 24 12.4	-31.394	-178.521	33.0	5.4	0.0	KERMADEC ISLANDS REGION
1989 269 21 24 56.8	-50.057	114.151	10.0	5.2	5.2	SOUTH OF AUSTRALIA
1989 271 21 52 17.1	20.329	98.822	10.0	5.4	5.7	BURMA
1989 272 19 24 44.0	-15.860	98.038	10.0	5.4	4.8	SOUTH INDIAN OCEAN
1989 273 04 16 45.5	-6.173	149.815	50.0	5.1	4.9	NEW BRITAIN REGION
1989 273 18 19 23.3	20.236	98.848	13.0	5.3	5.6	BURMA
1989 274 02 59 06.3	30.960	51.421	41.0	5.2	4.7	IRAN
1989 274 03 16 54.9	-6.562	130.098	155.0	5.3	0.0	BANDA SEA
1989 274 08 42 58.1	8.402	-82.763	35.0	5.1	4.0	PANAMA-COSTA RICA BORDER
1989 274 19 14 32.2	-7.546	154.775	36.0	5.2	0.0	SOLOMON ISLANDS
1989 275 07 55 40.7	10.531	126.918	25.0	5.4	4.5	PHILIPPINE ISLANDS REGION
1989 276 05 13 53.8	-7.084	146.049	185.0	5.2	0.0	EAST PAPUA NEW GUINEA
1989 276 15 21 44.1	-5.548	147.455	180.0	5.3	0.0	EAST PAPUA NEW GUINEA
1989 276 21 33 34.8	-24.103	-66.891	154.0	5.4	0.0	SALTA PROVINCE, ARGENTINA
1989 276 23 09 53.9	80.638	121.761	31.0	5.2	4.9	EAST OF SEVERNAYA ZEMLYA
1989 277 12 17 39.0	46.844	153.963	37.0	5.5	5.0	KURIL ISLANDS
1989 280 06 55 41.2	-20.095	169.023	38.0	5.5	5.7	VANUATU ISLANDS
1989 280 13 21 05.4	12.146	125.553	56.0	5.2	4.6	SAMAR, PHILIPPINE ISLANDS
1989 280 15 48 29.1	51.314	-179.028	19.0	6.1	6.7	ANDREANOF IS., ALEUTIAN IS.
1989 280 16 42 30.8	51.188	-179.234	33.0	5.7	5.9	ANDREANOF IS., ALEUTIAN IS.
1989 280 16 53 59.2	51.063	-179.149	33.0	5.2	0.0	ANDREANOF IS., ALEUTIAN IS.
1989 280 17 42 36.5	51.137	-179.221	33.0	5.6	5.7	ANDREANOF IS., ALEUTIAN IS.
1989 280 17 52 47.3	51.115	-179.241	33.0	5.5	5.6	ANDREANOF IS., ALEUTIAN IS.
1989 280 18 50 40.8	51.076	-179.306	33.0	5.5	5.3	ANDREANOF IS., ALEUTIAN IS.
1989 282 10 03 19.5	-4.293	-77.563	35.0	5.4	5.1	NORTHERN PERU
1989 282 18 01 07.9	51.780	171.869	26.0	6.0	5.3	NEAR ISLANDS, ALEUTIAN IS.
1989 282 20 39 40.2	-4.230	136.720	33.0	5.2	4.5	WEST IRIAN REGION
1989 283 06 04 45.0	-70.333	-114.992	10.0	5.3	0.0	SOUTHERN PACIFIC OCEAN
1989 283 06 45 38.1	-9.112	113.201	49.0	5.2	4.2	SOUTH OF JAVA
1989 284 14 55 52.6	-8.848	160.772	67.0	4.8	0.0	SOLOMON ISLANDS
1989 286 09 59 12.0	-17.609	122.404	10.0	5.4	4.5	WESTERN AUSTRALIA
1989 286 11 00 06.8	-18.158	-178.496	598.0	5.2	0.0	FIJI ISLANDS REGION
1989 286 16 49 36.9	-32.766	-179.009	100.0	5.5	0.0	SOUTH OF KERMADEC ISLANDS
1989 286 20 12 36.2	-30.433	-177.919	58.0	5.4	0.0	KERMADEC ISLANDS
1989 286 21 19 58.0	34.726	139.531	25.0	5.3	4.8	NEAR COAST OF HONSHU, JAPAN
1989 286 21 40 17.6	-16.010	-173.328	126.0	5.4	0.0	TONGA ISLANDS
1989 287 01 55 45.3	-3.359	152.085	400.0	5.3	0.0	NEW IRELAND REGION
1989 287 02 32 01.3	-24.256	-179.906	511.0	5.4	0.0	SOUTH OF FIJI ISLANDS
1989 288 10 05 04.8	-60.320	150.091	10.0	5.2	5.8	WEST OF MACQUARIE ISLAND
1989 288 21 12 04.1	19.151	121.197	33.0	5.2	4.6	PHILIPPINE ISLANDS
1989 289 14 45 37.5	-22.297	171.432	88.0	5.1	0.0	LOYALTY ISLANDS
1989 290 16 27 52.9	-4.035	152.407	25.0	5.6	5.8	NEW BRITAIN REGION
1989 291 00 04 15.2	37.036	-121.883	18.0	6.5	7.1	CENTRAL CALIFORNIA
1989 291 10 41 43.7	14.504	-45.225	10.0	5.2	0.0	NORTH ATLANTIC RIDGE
1989 291 11 40 50.2	-10.155	161.063	45.0	6.1	5.7	SOLOMON ISLANDS
1989 291 12 35 17.0	-10.183	161.113	69.0	5.4	0.0	SOLOMON ISLANDS
1989 291 13 06 47.8	14.603	-45.068	10.0	5.2	5.2	NORTH ATLANTIC RIDGE
1989 291 14 57 22.5	39.893	113.884	10.0	5.1	5.3	NORTHEASTERN CHINA
1989 291 16 19 02.8	-18.016	-176.328	208.0	5.4	0.0	FIJI ISLANDS
1989 291 17 01 35.0	39.985	113.990	10.0	5.2	5.6	NORTHEASTERN CHINA
1989 291 18 20 47.6	40.046	113.927	10.0	5.4	5.2	NORTHEASTERN CHINA

1989 291 18 41 24.3	2.086	126.579	53.0	5.2	4.8	MOLUCCA PASSAGE
1989 292 09 49 57.3	49.937	78.972	0.0	6.0	4.5	EASTERN KAZAKH SSR
1989 292 16 47 06.9	8.045	126.781	74.0	5.1	0.0	MINDANAO, PHILIPPINE ISLANDS
1989 293 03 43 13.2	0.573	121.435	102.0	5.4	0.0	MINAHASSA PENINSULA
1989 293 04 03 29.6	12.494	141.883	38.0	5.3	0.0	SOUTH OF MARIANA ISLANDS
1989 293 04 53 22.1	12.472	141.873	40.0	5.1	4.8	SOUTH OF MARIANA ISLANDS
1989 293 07 43 34.5	-0.024	123.156	153.0	5.4	0.0	MINAHASSA PENINSULA
1989 293 07 58 59.9	51.223	-179.108	33.0	5.1	0.0	ANDREANOF IS., ALEUTIAN IS.
1989 293 14 37 11.3	12.458	141.911	45.0	0.0	4.4	SOUTH OF MARIANA ISLANDS
1989 294 03 29 34.0	-5.272	68.542	10.0	5.1	5.2	CHAGOS ARCHIPELAGO REGION
1989 294 06 14 50.7	-26.082	-179.884	444.0	5.2	0.0	SOUTH OF FIJI ISLANDS
1989 294 12 44 59.8	-5.443	131.055	33.0	5.3	0.0	BANDA SEA
1989 295 02 10 57.5	26.304	-110.377	10.0	5.3	0.0	GULF OF CALIFORNIA
1989 295 13 24 15.1	-4.675	153.240	67.0	5.4	0.0	NEW IRELAND REGION
1989 295 20 35 40.9	-7.358	128.598	155.0	5.4	0.0	BANDA SEA
1989 296 03 30 41.9	-30.875	-65.441	170.0	5.2	0.0	CORDOBA PROVINCE, ARGENTINA
1989 296 13 08 25.6	-25.645	179.809	441.0	5.7	0.0	SOUTH OF FIJI ISLANDS
1989 296 13 19 36.8	39.865	113.900	33.0	5.3	0.0	NORTHEASTERN CHINA
1989 296 23 41 26.3	-27.916	-66.856	167.0	5.4	0.0	CATAMARCA PROVINCE, ARGENTINA
1989 297 16 29 58.2	-21.908	-138.977	0.0	5.4	0.0	TUAMOTU ARCHLPELAGO REGION
1989 298 06 46 42.7	-7.151	113.247	41.0	5.0	4.4	JAVA
1989 298 20 29 00.1	57.519	118.811	21.0	5.4	5.5	EAST OF LAKE BAIKAL
1989 299 01 45 58.7	39.709	143.865	33.0	5.2	0.0	OFF E. COAST OF HONSHU, JAPAN
1989 299 14 34 33.6	-22.552	-176.895	185.0	5.1	0.0	SOUTH OF FIJI ISLANDS
1989 299 17 06 41.6	39.812	143.539	8.0	5.8	5.8	OFF E. COAST OF HONSHU, JAPAN
1989 299 17 53 06.5	39.821	143.963	10.0	3.2	0.0	OFF E. COAST OF HONSHU, JAPAN
1989 299 21 39 22.9	-4.651	152.828	74.0	5.4	0.0	NEW BRITAIN REGION
1989 300 01 45 55.1	39.823	143.692	9.0	5.8	6.2	OFF E. COAST OF HONSHU, JAPAN
1989 300 02 06 08.1	39.752	143.602	10.0	5.3	0.0	OFF E. COAST OF HONSHU, JAPAN
1989 300 04 39 30.6	-20.893	-173.968	33.0	5.1	5.3	TONGA ISLANDS
1989 300 21 04 51.8	-11.022	162.350	24.0	6.1	7.0	SOLOMON ISLANDS
1989 302 03 09 10.7	39.590	143.458	10.0	5.7	5.9	OFF E. COAST OF HONSHU, JAPAN
1989 302 05 25 38.3	39.571	143.333	9.0	6.0	6.6	OFF E. COAST OF HONSHU, JAPAN
1989 302 10 51 25.3	39.500	143.408	18.0	5.2	5.3	OFF E. COAST OF HONSHU, JAPAN
1989 302 15 53 10.7	39.531	143.412	10.0	5.4	5.3	OFF E. COAST OF HONSHU, JAPAN
1989 302 19 09 12.9	36.788	2.448	5.0	5.7	5.7	ALGERIA
1989 302 19 21 52.4	36.745	2.443	10.0	5.4	5.6	ALGERIA
1989 303 23 46 30.6	-21.104	-178.684	582.0	5.6	0.0	FIJI ISLANDS REGION
1989 304 07 18 48.9	-11.009	162.397	50.0	5.1	4.5	SOLOMON ISLANDS REGION
1989 304 15 30 00.1	37.263	-116.491	0.0	5.7	0.0	SOUTHERN NEVADA
1989 304 16 56 58.5	-21.826	-138.910	0.0	5.2	0.0	TUAMOTU ARCHIPELAGO REGION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