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# MODERN SEISMIC TRAVEL TIME TABLES AND STATION CORRECTIONS FOR P AND S WAVES

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**13. ABSTRACT** *(Maximum 200 words)*

1) We refine estimates of inner core structure by examining PKP travel times and find that anisotropy is a simpler explanation than heterogeneity for the observed residual patterns. Our preferred model of inner core anisotropy contains velocities that are 0.5% faster in a N-S direction than an E-W direction. 2) We study various mantle differential travel times including SS-S, ScS-S, PP-P, and PcP-P and compare these results to those obtained from handpicked waveform data. Large-scale coherent patterns of residuals are seen which indicate mantle heterogeneity. 3) We examine PKP travel times to study the possibility of outer core heterogeneity models which are suggested by observations of anomalous splitting in normal modes. We find that the travel times limit the scale of possible outer core heterogeneity to models much smaller than those required to explain the mode splitting data. 4) We develop computer codes which return travel time and ray geometries for a given seismic phase, source-receiver pair, and arbitrary 3-d earth models specified by their spherical harmonic expansions.

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## TASK OBJECTIVES

The broad objective of this research is to understand the mapping of seismic travel time data into the Earth's velocity structure. We are developing a self-consistent set of mantle and core velocity models and station corrections, utilizing all the available phase data in the ISC catalog. These models will provide AFOSR and AFTAC with a self-consistent Earth model for use in generating travel times for phase identification and event location.

Specifically, the work statement includes the following:

- Extension of radial model work to core and other mantle phases
    - Core phases *PKP*, *SKS*, and *PKIKP*
    - Better mantle *S* wave model from core phases
    - Multiple phases, such as *pP*, *sS*, *PP* and *SS*
    - Better control on source depth from depth phases
    - *PP* and *SS* residual patterns to find bouncepoint "correction"
    - Core reflected phases *PcP* and *ScS*
    - Inversion of all ISC phase data for improved radial earth model

- Computer program for travel time curves
    - Program to give ray geometry for given source-receiver pair
    - Distribute program on various media for general use

## TECHNICAL RESULTS

## ABSTRACT

In this report we present the results of several investigations dealing with different topics:

- We refine estimates of inner core structure by examining differential *PKP* travel times and find that anisotropy is a simpler explanation than heterogeneity fot the observed residual patterns. Our preferred model of inner core anisotropy contains velocities that are 0.5% faster in a N-S direction that an E-W direction.

- We study various mantle differential travel times including *SS–S*, *ScS–S*, *PP–P*, and *PcP–P* and compare these results to those obtained from handpicked waveform data. Large-scale coherent patterns of residuals are seen which indicate mantle heterogeneity.

- We examine *PKP* travel times to study the possibility of outer core heterogeneity models which are suggested by observations of anomalous splitting in normal modes. We find that the travel times limit the scale of possible outer core heterogeneity to models much smaller than those required to explain the mode splitting data.

- We develop computer codes which return travel time and ray geometries for a given seismic phase, source-receiver pair, and arbitrary 3-d earth models specified by their spherical harmonic expansions.

## PART 1: INNER CORE STRUCTURE

We have estimated inner core anisotropy by examining differential *PKP* travel times. *PKP(BC)* versus *PKP(DF)* travel times show coherent patterns of residuals indicating aspherical structure within the Earth's inner core. Figure 1 shows 19,470 probable *BC* versus *DF* travel times at ranges between 145° and 155° obtained from 23 years of the ISC catalog. These times were obtained by finding the difference between any pairs of picks within a time window around the predicted *PKP* arrival times. The diagonal banding results from the 0.1 s resolution of the ISC picks and the tendency for operators to pick even seconds or half seconds. A hint of the *AB* branch can be seen sloping away near 148° range. Using a bin averaging scheme in which points on a sphere are combined within 416 approximately equal area cells we produced plots of average residual versus turning point position (Figure 2) and versus ray direction (Figure 3). Positive residuals are indicated with crosses and negative residuals with diamonds; the size of the symbol indicates the magnitude of the residual. The turning point position plot is most sensitive to inner core heterogeneity, while the ray angle plot is most sensitive to inner core anisotropy. Large positive residuals are seen near the poles in the ray-direction plot, indicating fast N-S inner core velocities. This result is in agreement with previous studies of absolute *PKP* residuals but derived from an independent data set. Due to the sparse ray coverage of our data, either heterogeneity of anisotropy within the inner core with about 1% velocity variations could explain the residual patterns seen in Figures 2 and 3. However, inversions of the ISC data for heterogeneity require many more free parameters to achieve the same variance reduction as a simple 2 parameter anisotropy model.

Shearer, P.M., and K.M. Toy, 1991, PKP(BC) versus PKP(DF) differential travel times and aspherical structure in the Earth's inner core, *J. Geophys. Res.*, 96, 2233-2247.

## PART 2: DIFFERENTIAL TRAVEL TIMES

We copied the ISC travel times into a condensed binary format which provides on-line access to the data from our HP/Apollo computer network. We have extracted *PP-P*, *SS-S*, *PcP-P*, and *ScS-S* differential travel times for further analysis and comparisons with results obtained for long-period data. The ISC data base from 1964 to 1987 currently contains over 9 million global travel times (Figure 4). By separating earthquake and station information and storing the data in binary (rather than ASCII), we have reduced the storage requirements of this data set to about 100 Mbytes, or slightly over 10 bytes per travel time. A data base of this size can be left on magnetic disk for convenient access. In addition, the use of binary block read and write statements means that the entire data set can be retrieved and stored in a matter of several minutes.

We have examined differential travel time pairs in the ISC data. Differential times have many advantages in travel time analyses since they are relatively insensitive to errors in earthquake depths and origin times. Figure 5 shows the results of extracting all pairs of arrivals at a single station in which one of the arrivals was within 20 s of the predicted *S*-wave travel time. Each point plotted is a differential time relative to the *S*-wave pick shown at zero time. Only shallow events (< 50 km) deep are shown to avoid complications due to depth phases. Many additional phases are apparent in this plot, including *PcS*, *ScS*, *SKS*, *PS*, *PPS*, *SS*, and *SSS*. We extracted 25,419 *SS* - *S* differential times and 20,821 *ScS* - *S* times from picks tabulated by the ISC from 1964 to 1987. This was done by identifying pairs of picks from a station for a particular event, where each pick is within 20 s of the predicted arrival time. These differential times exhibit much less scatter than absolute ISC travel times.

Figures 6 and 7 plot histograms of ISC *SS-S* and *ScS-S* differential times versus times obtained by Woodward and Masters (1991a,b) from long-period waveforms. Although the ISC data show more scatter, with suitable windowing, binning and averaging ISC differential times exhibit geographic patterns similar to those recently obtained from long-period GDSN data. This is illustrated in Figures 8-11 which plot differential travel time residuals versus bounce point positions for both the ISC and GDSN. Residuals have been smoothed by averaging within caps of 5° radius. Positive residuals are shown as triangles, negative residuals as crosses, with the size of the symbol proportional to the magnitude of the anomaly. Notice the coherent patterns of residuals in both data sets indicative of upper mantle heterogeneity in the case of *SS-S* and lowermost mantle heterogeneity and/or core-mantle-boundary topography in the case of *ScS-S*. This suggests that the ISC data can be used to map the shear velocity structure of the mantle, although the geographic coverage of the binned ISC data is less complete than that of the long-period data. For the binned and averaged data, plots of ISC versus long-period differential times show a correlation with approximately unit slope (Figure 12). The considerable scatter in these plots could be due to errors in the ISC picks not removed by the averaging scheme, or may reflect differences in long-period versus short-period travel times.

We also extracted 78,210 *PP-P* differential times and 119,810 *PcP-P* times from picks tabulated by the ISC from 1964 to 1987. This was done by identifying pairs of picks from a station for a particular event, where each pick is within 20 s of the predicted arrival time. As in the case of the S-waves, differential travel time residuals versus bounce point position show large-scale coherent patterns indicative of mantle heterogeneity. With suitable windowing, binning and averaging, ISC *PP-P* times exhibit geographic patterns similar to those recently obtained by Woodward and Masters (1991a) from long-period GDSN data. This suggests that the ISC data can be used to map the *P*-wave velocity structure of the upper mantle, although the geographic coverage of the binned ISC data is less complete than that of the long-period data. *PcP* can only very rarely be identified in long-period data so the ISC data provide the best available source of global *PcP* - *P* times.

Woodward, R.L., and G. Masters, 1991a, Global upper mantle structure from long-period differential travel times, *J. Geophys. Res.*, 96, 6351-6377.

Woodward, R.L., and G. Masters, 1991b, Lower-mantle structure from ScS-S differential travel times, *Nature*, 352, 231-233.

## PART 3: OUTER CORE STRUCTURE

Our goal was to use *PKP* travel time data from the International Seismological Centre (ISC) to constrain possible aspherical structure in Earth's outer core and compare these results with current analyses of anomalous splitting of normal modes which suggest such structure.

We examined travel times for core phases collected by the International Seismological Centre (ISC) from 1964 to 1987 in an attempt to either resolve or place upper bounds on hypothetical outer-core velocity structures. We extracted 50,297 *PKP(BC)* travel times (145° to 156° range), 15,286 *PKP(DF)* times (110° to 135°) and 16,963 *PKP(AB)* times (150° to 165 ). We excluded *PKP(DF)* at longer ranges to avoid contamination by possible inner-core structure. All picks were examined (i.e. the ISC phase identifications are discarded), corrected for ellipticity, and the Toy station corrections applied. The ISC earthquake locations and origin times were used; the events were not relocated. Zero depth events were excluded as well as picks which follow a likely P-wave pick on the same seismogram (this should eliminate most depth phases).

We binned the data into summary rays using 15° cells in turning point position and ray azimuth. A fairly coarse increment was used since the data are sparse and we are mostly interested in any low-order structure. Estimates for the residual within each bin were obtained by finding the peak in a heavily smoothed histogram of the residuals. Standard errors for these estimates were estimated with a bootstrap technique which randomly resamples the data. This method introduces less bias than simply computing the mean within some fixed window (which will tend to reduce the size of the anomaly).

Results of this procedure are shown in Figures 13-15. Positive residuals are shown in black (slow anomalies) and negative residuals are shown in gray (fast anomalies). The position of the turning point bin is indicated on the map, with the angle of the wedges showing the local ray azimuth at the turning points and the length of the wedge showing the size of the residual. Bins are only shown if the estimated standard error is less than 0.5 s. These plots reveal how sparse the ray coverage is (most of the turning point bins contain data from only one azimuth). However, there is coherence between adjacent summary rays suggesting that these times are indicative of structure in the mantle or core.

Recent analyses of anomalous splitting of normal mode spectral peaks (e.g., Ritzwoller *et al*., 1986; Widmer *et al*., 1992) have suggested the possibility of aspherical structure in Earth's outer core. The hypothesized models contain axi-symmetric velocity perturbations of spherical harmonic degree 2 in which velocities are about 0.5% faster near the poles than at the equator (i.e. a $C_{20}$ anomaly). These models predict travel time anomalies of several seconds in *PKP* phases which travel through the outer core. However, the *PKP* times plotted in Figures 13-15 do not exhibit obvious $C_{20}$ anomalies. Plots of predicted vs. actual PKP travel times show large scatter with no clear correlation. Figure 16 shows the change in misfit variance when the data are corrected for an outer core velocity model which can explain the anomalous splitting data. The solid line is for *PKP(DF)*, the long-dashed line for *PKP(BC)* and the short dashed line for *PKP(AB)*. The outer core model increases the data variance by 50 to 80%.

These results did not use any correction for mantle heterogeneity. We experimented with scaled versions of shear-wave models but found that these did not predict ISC *P*-wave residuals very well. Instead, we used LO2.56, the Harvard lower mantle *P*-wave model. Figure 17 shows the variance change which results when this model is applied to *P* and *PKP* data. The *P* analysis used 35,300 picks from 85 to 100°, binned and averaged exactly the same way as the *PKP* data. LO2.56 reduced the variance of these data by about 20%. The best variance reduction for *P* was achieved with a scaling of unity, indicating that the model amplitude is about right. The results for *P* are reassuring since LO2.56 is based on ISC *P*-wave data; however it is somewhat disturbing that a greater variance reduction is not achieved. Figure 17 also shows the results of applying this model to *PKP* data – the variance of these data are increased by 40 to 50%. A tiny variance reduction can be achieved if LO2.56 is reduced in size by about a factor of 5.

As an experiment, we went ahead and applied a correction to the *PKP* times based on the full LO2.56 model. However in light of the large variance increase that results, it is questionable whether this should be done. Figure 18 is analogous to Figure 16 and shows the variance change as a function of $C_{20}$ anomaly size for the LO2.56 corrected data. The mantle corrections do not have a large affect on the results.

Our analysis of PKP travel times from the ISC found that they appear inconsistent with outer core velocity anomalies of the size required to explain anomalous mode splitting data. We are currently exploring the effect of confining the anomaly to particular depth ranges within the outer core. Preliminary results indicate that the ISC data are less inconsistent with models in which the anomaly is confined to near the surface of the outer core, but that this improvement is nevertheless too small to reconcile the travel time and mode data. We are also experimenting with outer core anisotropy models and higher order heterogeneity models. However, so far the source of the bulk of the anomalous mode splitting remains unknown.

The need to correct core phase data for the effects of mantle heterogeneity is a problem in these analyses. Most of the coherent signal in *PKP* data is probably due to mantle heterogeneity; however current mantle models do not account for the signal. This is most likely due to limitations in the mantle models rather than an indication of core structure. A promising approach for future analyses will be to include both *P* and *PKP* data in inversions for mantle velocity structure to see if a model can be found which is consistent with both data sets.

Ritzwoller, M., G. Masters, and F. Gilbert, 1986, Observations of anomalous splitting and their interpretation in terms of aspherical structure, *J. Geophys. Res.*, **91**, 10203-10228.

Widmer, R., G. Masters, and F. Gilbert, 1992, Observably split multiplets—data analysis and interpretation in terms of large-scale aspherical structure, *Geophys. J. Int.*, **111**, 559-576.

## PART 4: SOFTWARE DEVELOPMENT

We have developed computer programs to return travel time and ray geometries for a given seismic phase and source-receiver pair. For speed and convenience we have implemented a set of subroutines for the radially symmetric earth which interpolate travel times from a set of tables. We have computed these tables for dozens of seismic phases using both PREM and the new IASPEI91 earth models. In addition, we have digitized the JB tables for most of the major phases. We have written a subroutine, GET_TT, which automatically returns a travel time for a given phase name, range, and source depth. We have incorporated this subroutine in our data analysis software here at IGPP.

We have written a subroutine, GET_PATH, which returns a ray path (specified by depth, range and accumulated travel time at 10 km depth increments) for a given phase name, range and source depth. We have also implemented a subroutine, GET_PERT, which returns the accumulated travel time anomaly for ray paths determined from GET_PATH and global 3-d earth models specified by their spherical harmonic expansions. We have implemented these routines for several mantle models (e.g. LO2.56, M84c, sh.10c.17, MDSLH) after putting them into a standard format. These subroutines will be incorporated into our data analysis software here at IGPP, such that as a seismogram is displayed on the screen the predicted travel times for all major seismic phases for any 3-d earth model will also be shown for comparison purposes.

## Figures

**Figure 1.** *PKP(BC) – PKP(DF)* differential travel time residuals from ISC data plotted as a function of range. No points are found in the lower left corner due to the impossibility of observing negative *BC – DF* times (the first arrival is always assumed to be *DF*). Notice that ISC picks are to the nearest 0.1 s and that operators tend to pick even seconds and half seconds; this causes the pronounced diagonal banding in the data.

**Figure 2.** ISC differential *PKP(BC) - PKP(DF)* travel time residuals plotted on a map of turning point position. Data have been binned and averaged into approximately equal area bins, with a minimum of three rays required in each averaging bin.

**Figure 3.** ISC differential *PKP(BC) - PKP(DF)* travel time residuals plotted on a map of ray direction at the turning point. Note the generally positive residuals near the north and south poles. The slight deviations from 180° symmetry result from asymmetries in the binning scheme.

**Figure 4.** ISC travel times from 1964 to 1987 for shallow events (<50 km).

**Figure 5.** ISC travel times relative to an *S*-wave pick within 20 s of the theoretical *S* arrival time. Only shallow events are plotted (<50 km).

**Figure 6.** Histograms of *SS-S* residuals obtained from long-period GDSN waveforms (left) and ISC picks (right).

**Figure 7.** Histograms of *ScS-S* residuals obtained from long-period GDSN waveforms (left) and ISC picks (right).

**Figure 8.** ISC *SS-S* residuals binned and averaged in 5° radius caps by turning point position. Negative (fast) anomalies are shown as triangles; positive (slow) anomalies are shown as plus signs.

**Figure 9.** GDSN *SS-S* residuals binned and averaged in 5° radius caps by turning point position. Negative (fast) anomalies are shown as triangles; positive (slow) anomalies are shown as plus signs.

**Figure 10.** ISC *ScS-S* residuals binned and averaged in 5° radius caps by turning point position. Negative (fast) anomalies are shown as triangles; positive (slow) anomalies are shown as plus signs.

**Figure 11.** GDSN *ScS-S* residuals binned and averaged in 5° radius caps by turning point position. Negative (fast) anomalies are shown as triangles; positive (slow) anomalies are shown as plus signs.

**Figure 12.** ISC versus GDSN differential time residuals for *SS-S* and *ScS-S* (right).

**Figure 13.** *PKP(BC)* residuals binned and plotted at turning point location. Positive (slow) anomalies are shown as black, negative (fast) anomalies as gray. Azimuth of ray at turning point is indicated by the angle of the plot. Only residuals with estimated standard errors less than 0.5 s are plotted.

**Figure 14.** *PKP(DF)* residuals binned and plotted at turning point location. Positive (slow) anomalies are shown as black, negative (fast) anomalies as gray. Azimuth of ray at turning point is indicated by the angle of the plot. Only residuals with estimated standard errors less than 0.5 s are plotted.

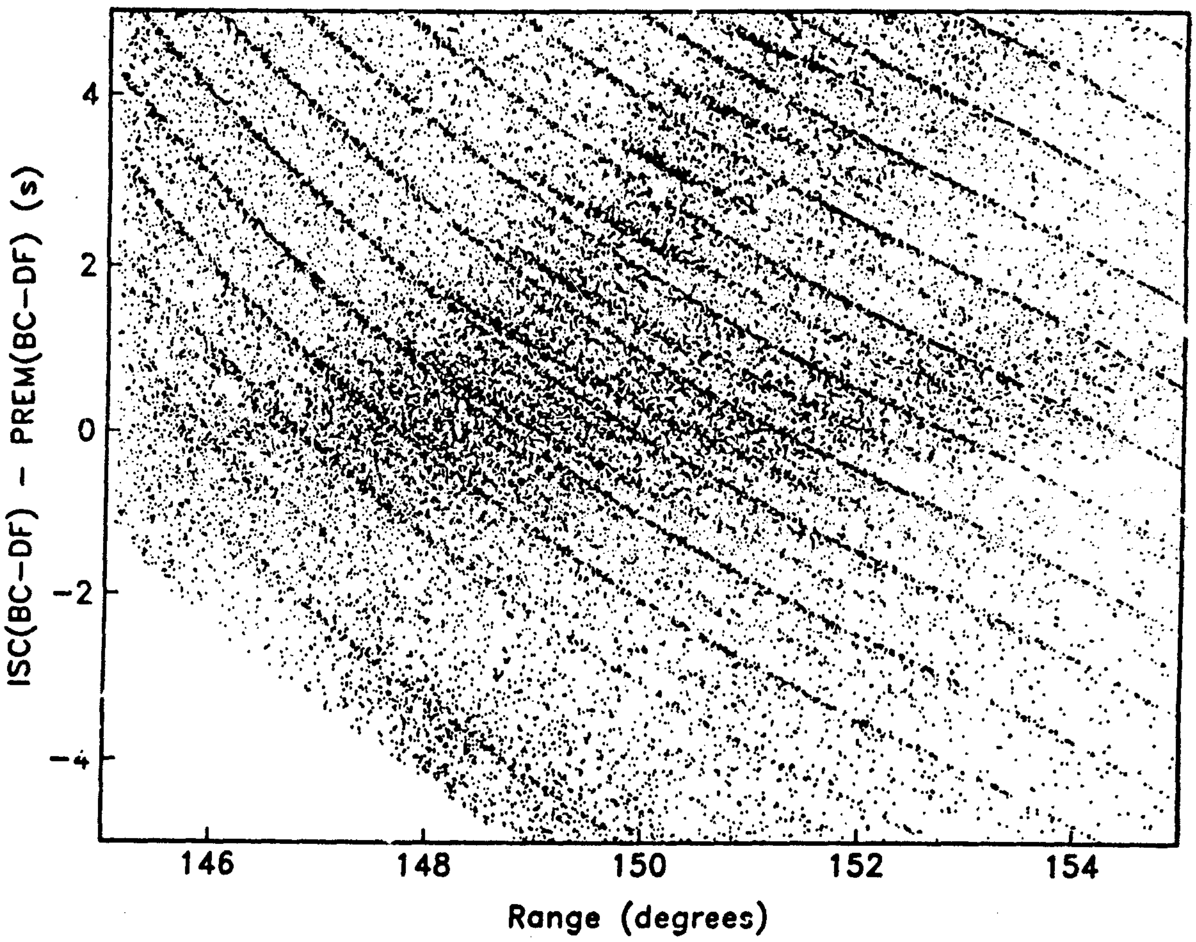
**Figure 15.** *PKP(AB)* residuals binned and plotted at turning point location. Positive (slow) anomalies are shown as black, negative (fast) anomalies as gray. Azimuth of ray at turning point is indicated by the angle of the plot. Only residuals with estimated standard errors less than 0.5 s are plotted.

**Figure 16.** Variance of misfit to ISC residual bins as a function of relative size of outer core $C_{20}$ velocity heterogeneity. *PKP(DF)* is shown as a solid line, *PKP(BC)* as a dashed line, and *PKP(AB)* as a dotted line. A $C_{20}$ anomaly which can explain the mode splitting data (scaled to a relative size of unity) increases the variance of the ISC data by 50 to 80%.

**Figure 17.** Variance of misfit to ISC residual bins as a function of the relative size of the mantle heterogeneity model LO2.56. This model improves the fit to the *P*-wave data but increases the scatter in *PKP* travel times.

**Figure 18.** Variance of misfit to LO2.56 corrected ISC residual bins as a function of relative size of outer core $C_{20}$ velocity heterogeneity. *PKP(DF)* is shown as a solid line, *PKP(BC)* as a dashed line, and *PKP(AB)* as a dotted line. The mantle corrections do not greatly change the results (compare Figures 16 and 18).

PKP(BC) – PKP(DF) Differential Travel-Time Residuals (ISC–PREM)



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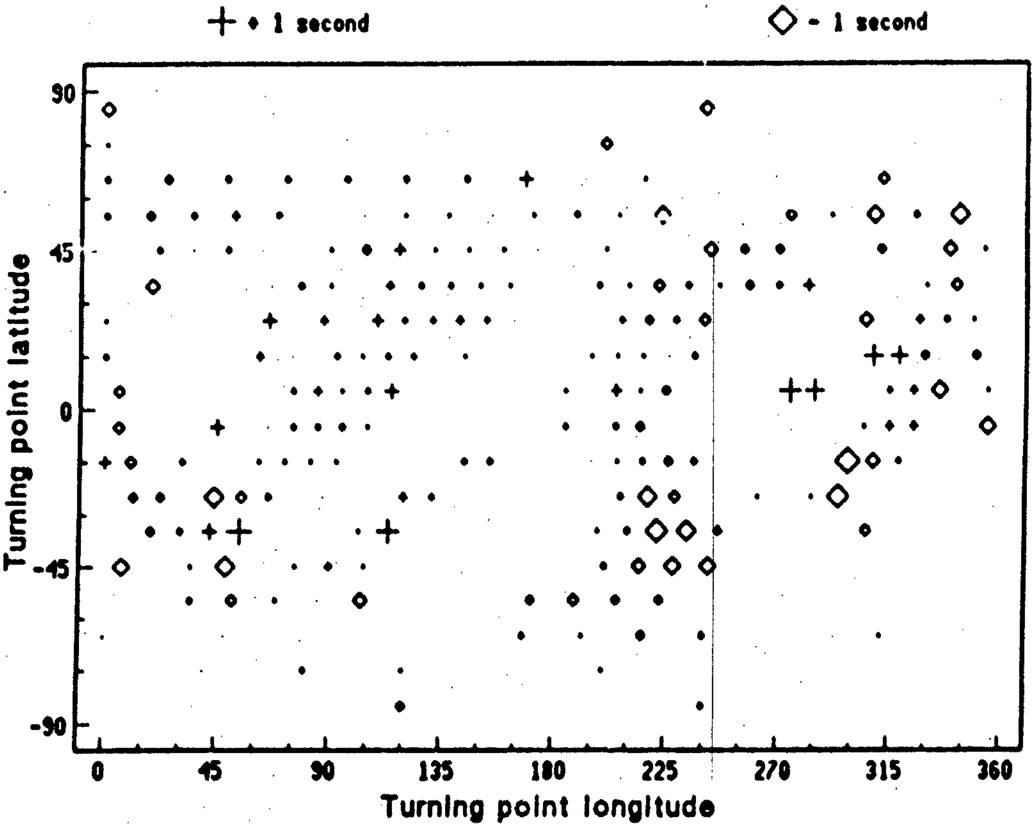

+ + 1 second
◇ - 1 second
90
45
0
-45
-90
Turning point latitude
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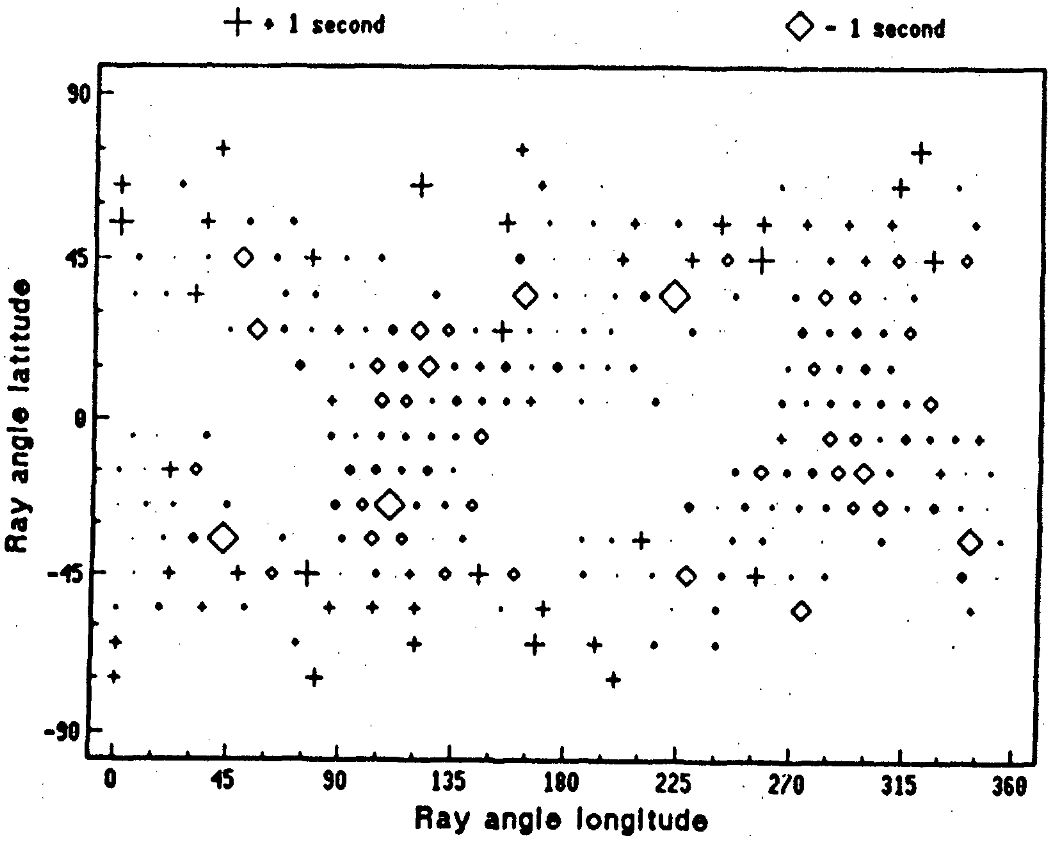
45
90
135
180
225
270
315
360
Turning point longitude

Figure 2.


+ + 1 second
◇ - 1 second
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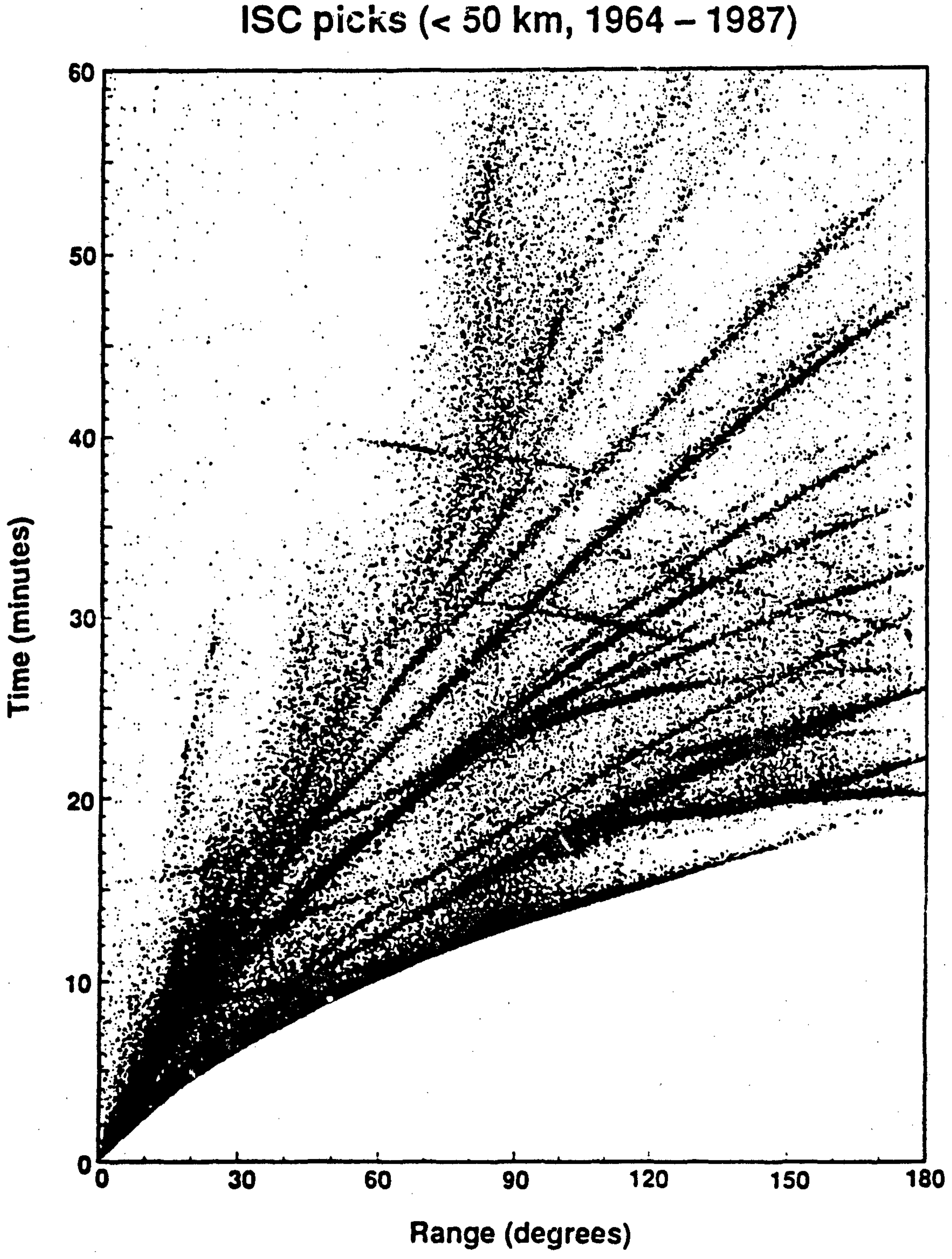
Ray angle latitude
Ray angle longitude

Figure 3.


ISC picks (< 50 km, 1964 – 1987)
Time (minutes)
Range (degrees)
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20
30
40
50
60
0
30
60
90
120
150
180

Figure 4.

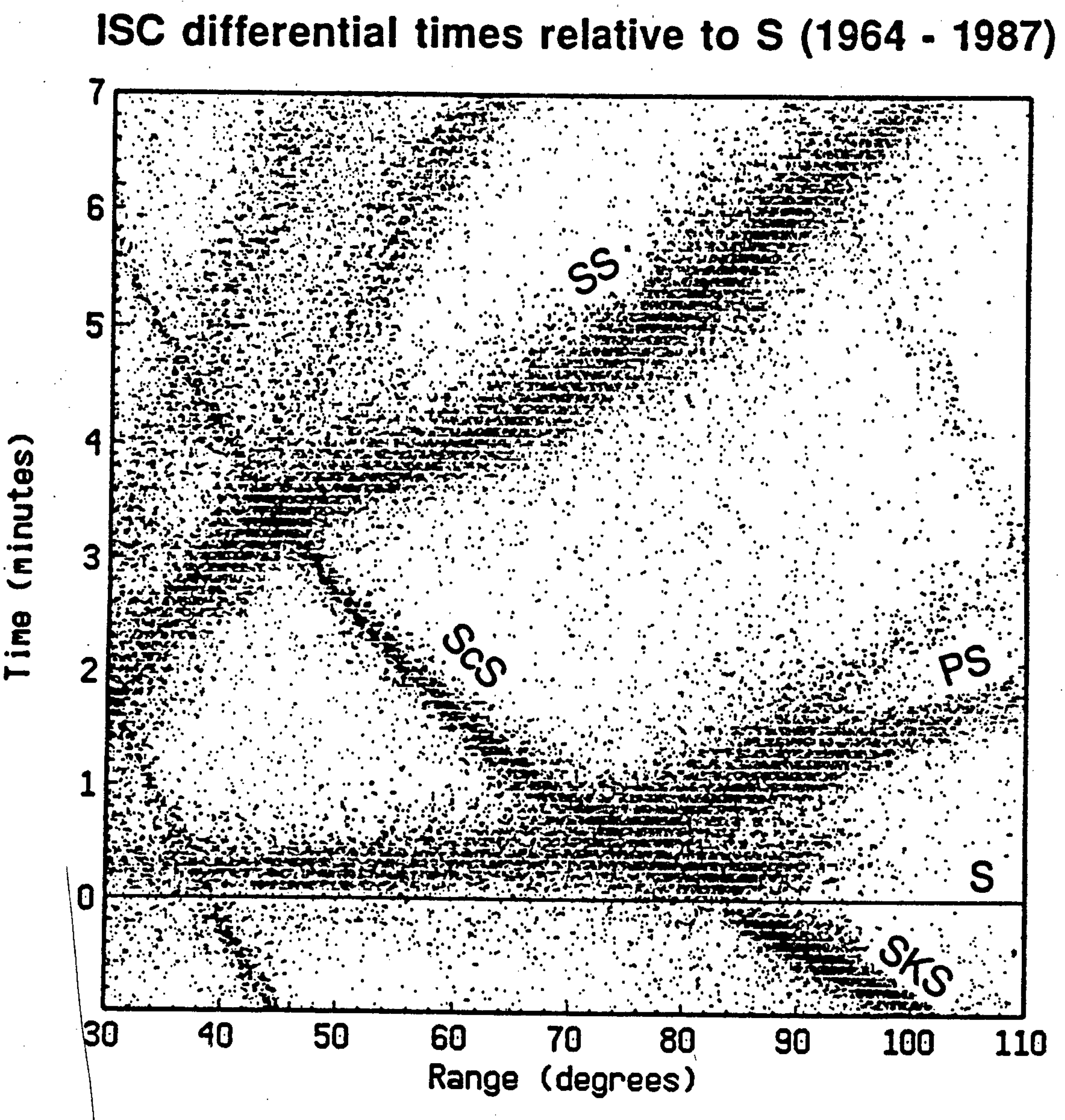
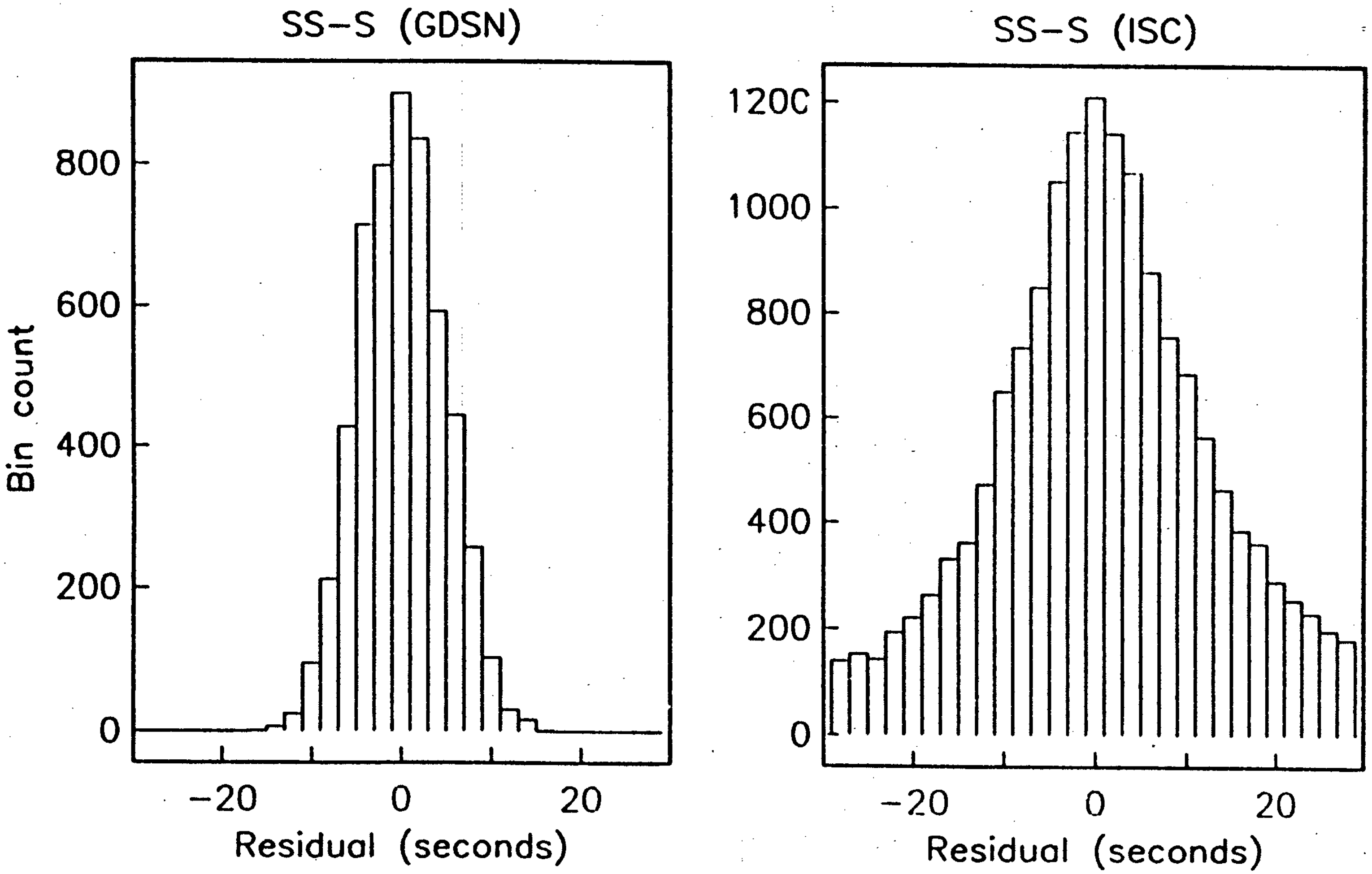

ISC differential times relative to S (1964 - 1987)
Time (minutes)
7
6
5
4
3
2
1
0
SS
ScS
PS
S
SKS
30
40
50
60
70
80
90
100
110
Range (degrees)

**Figure 5.**


SS–S (GDSN)
Bin count
800
600
400
200
0
−20
0
20
Residual (seconds)
SS–S (ISC)
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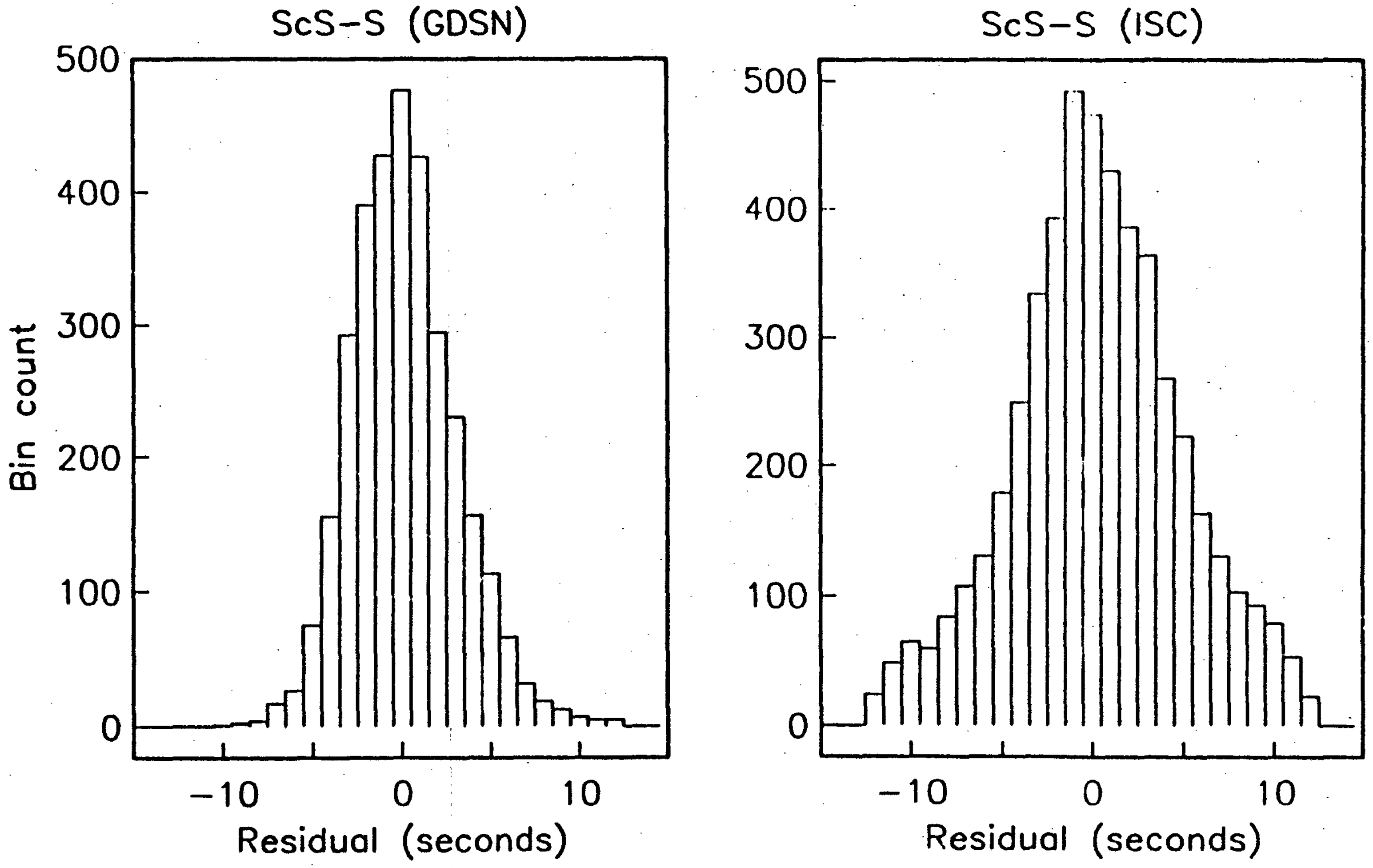
1000
800
600
400
200
0
−20
0
20
Residual (seconds)

Figure 6.


ScS–S (GDSN)
ScS–S (ISC)
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200
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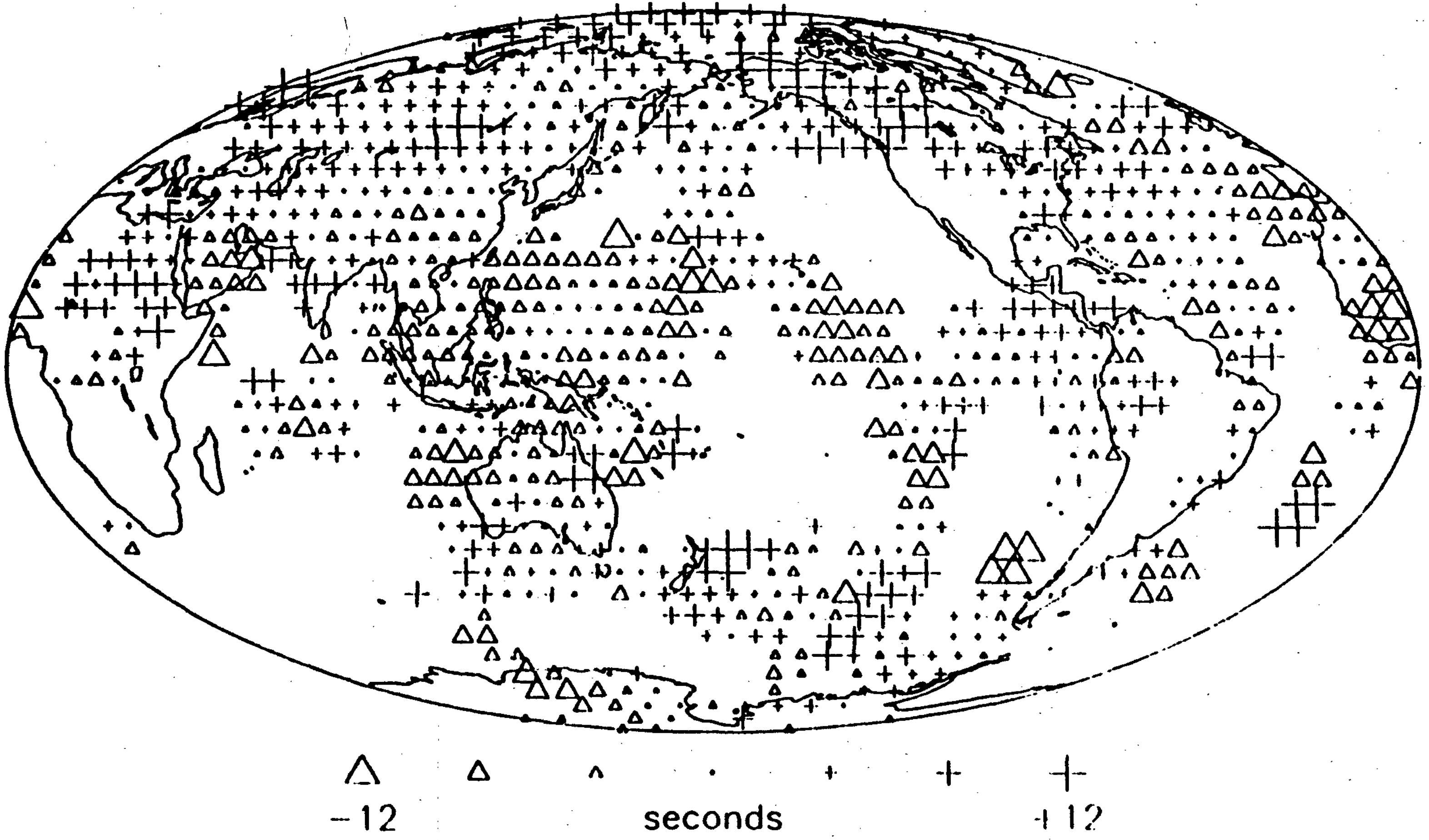
0
–10
0
10
Residual (seconds)

Figure 7.



SS-S times from ISC (cap averages)

Figure 8.

SS-S times from GDSN waveforms (cap averages)

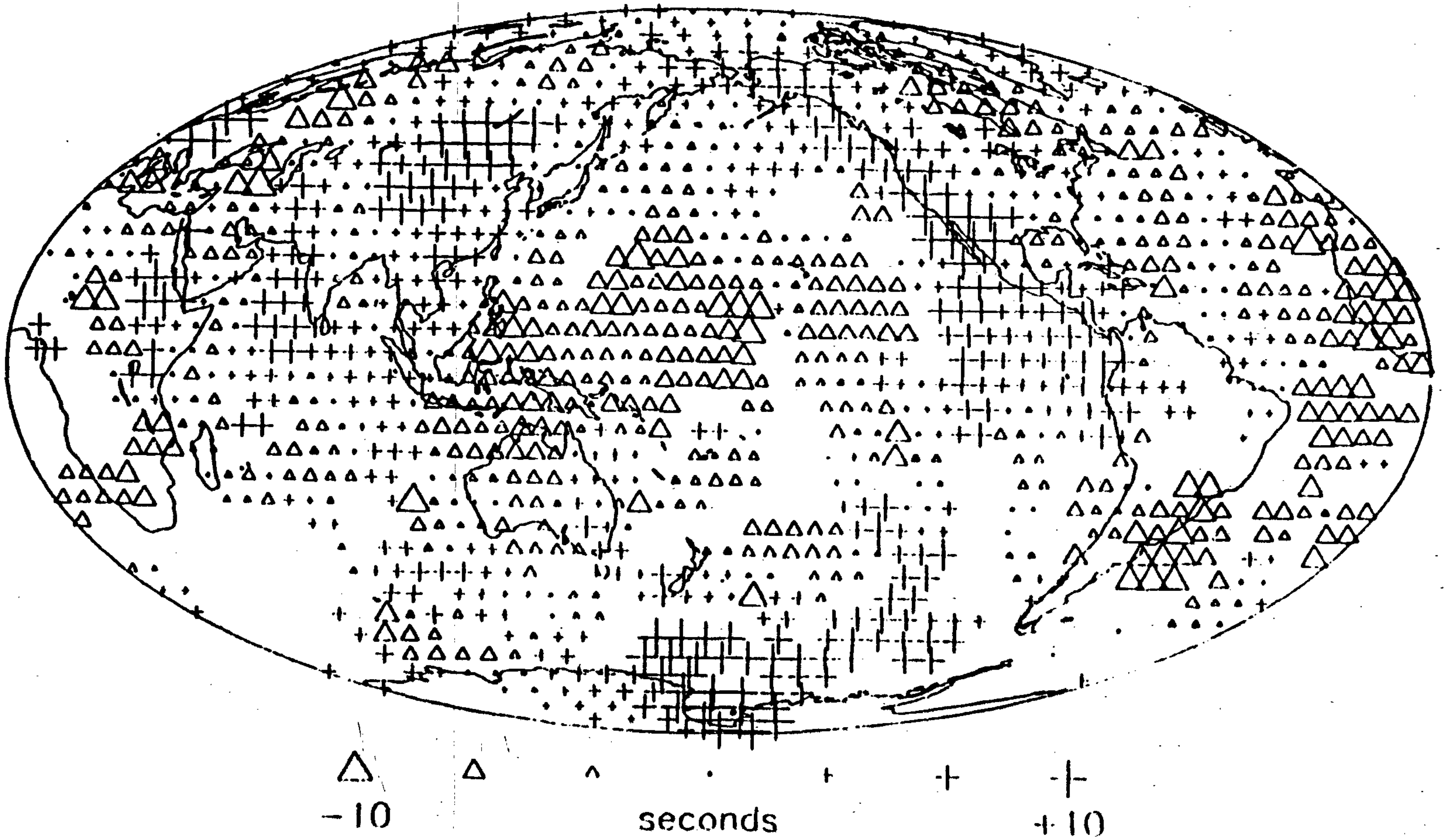
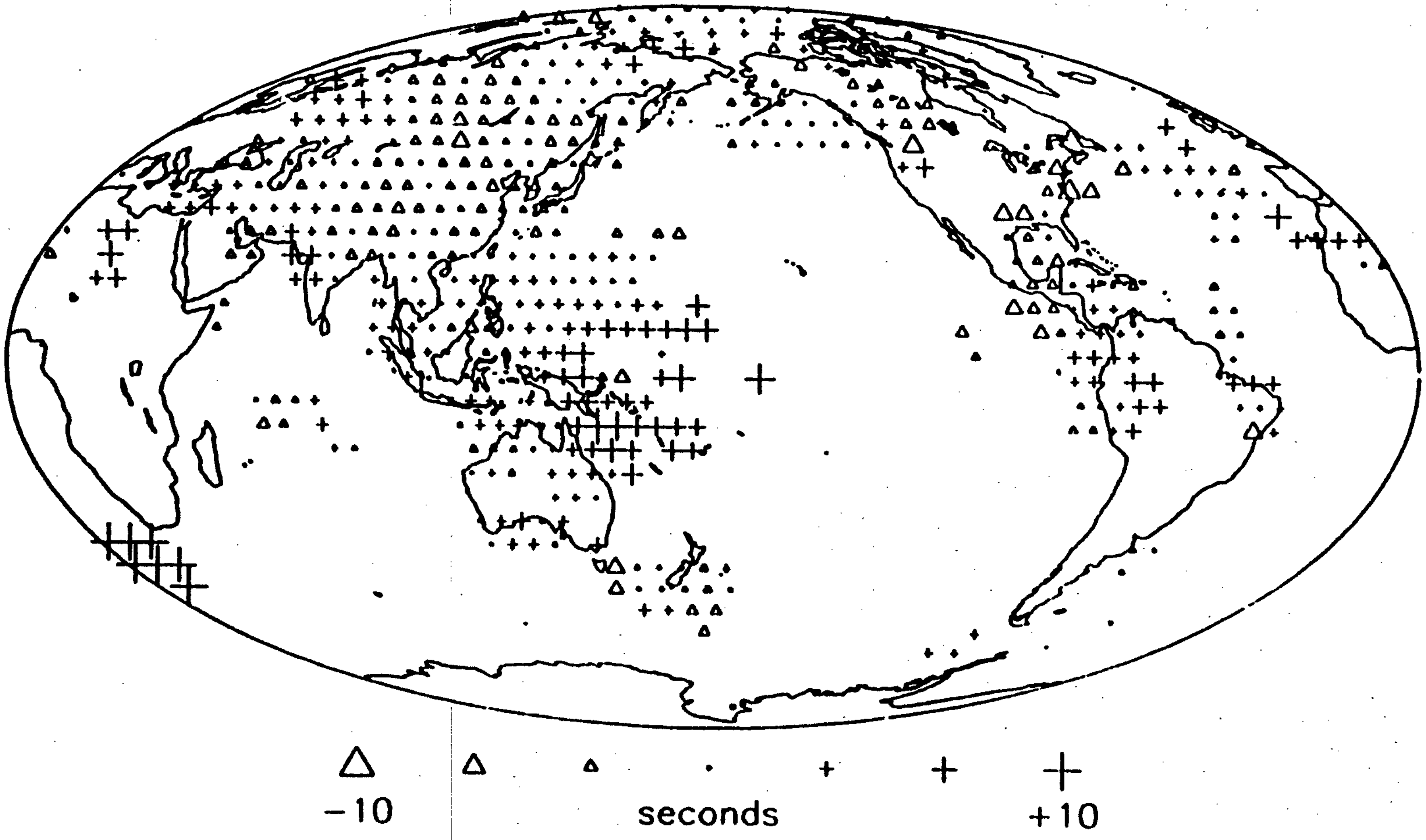


Figure 9.



ScS-S times from ISC (cap averages)

Figure 10.

ScS-S times from GDSN waveforms (cap averages)

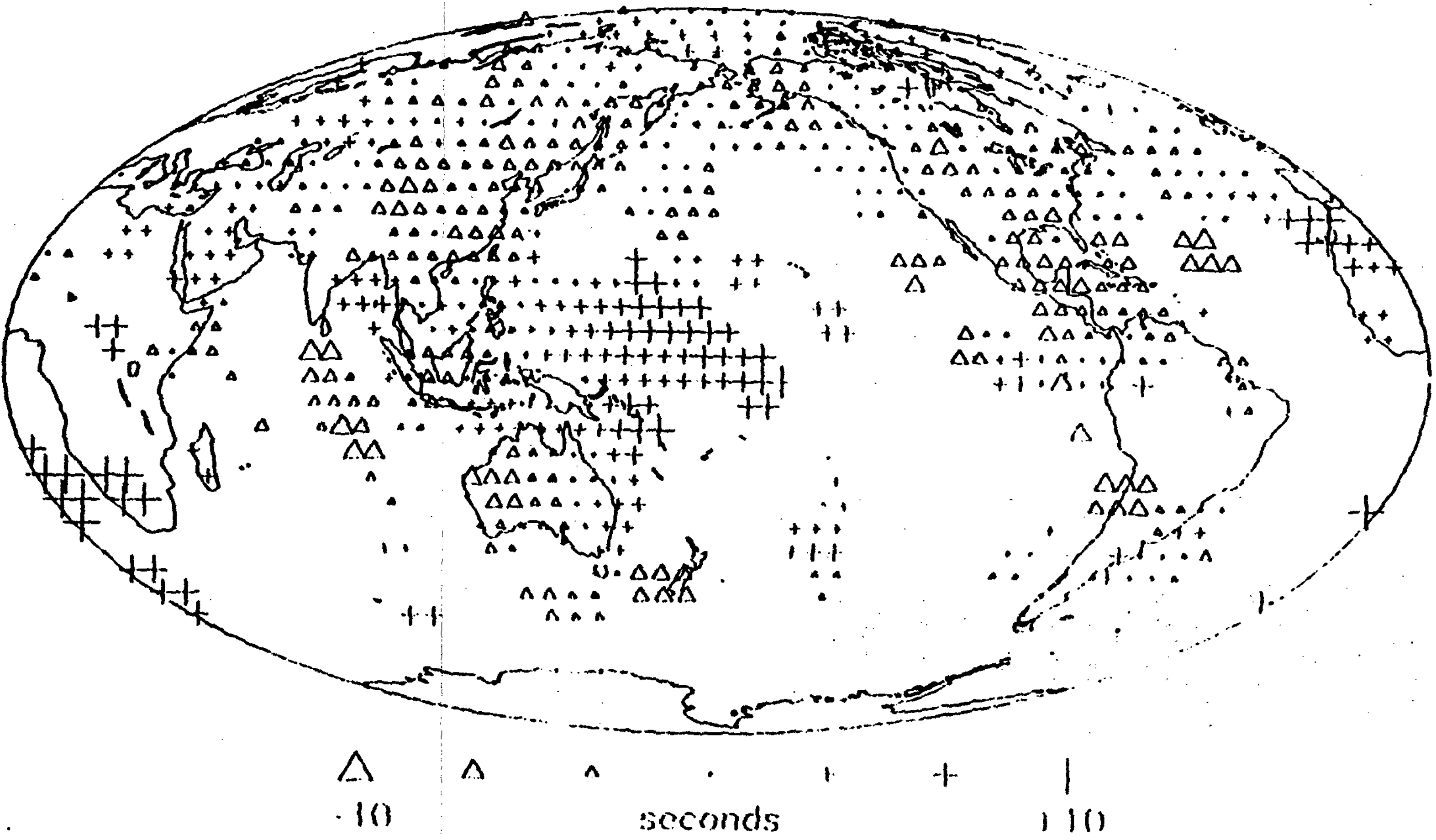
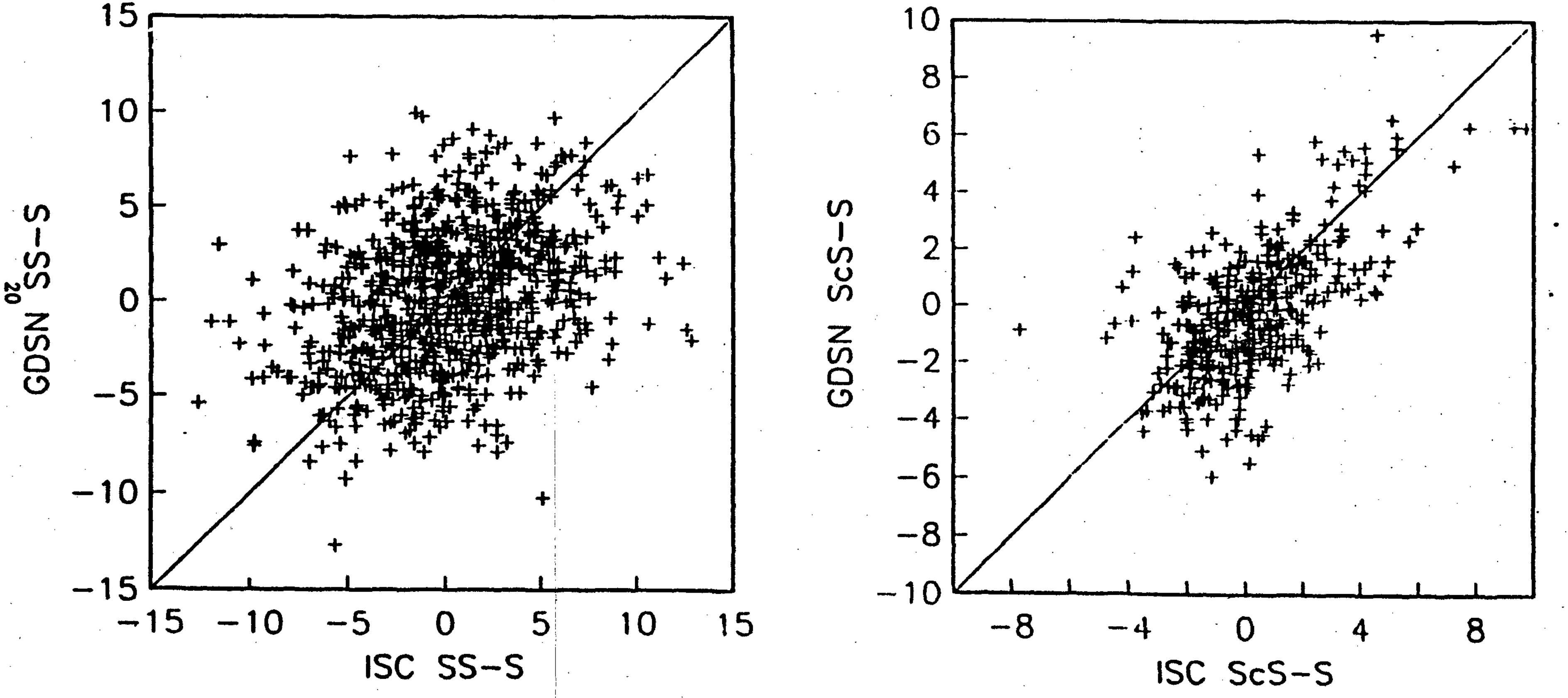


Figure 11.

GDSN versus ISC differential times (cap averages)



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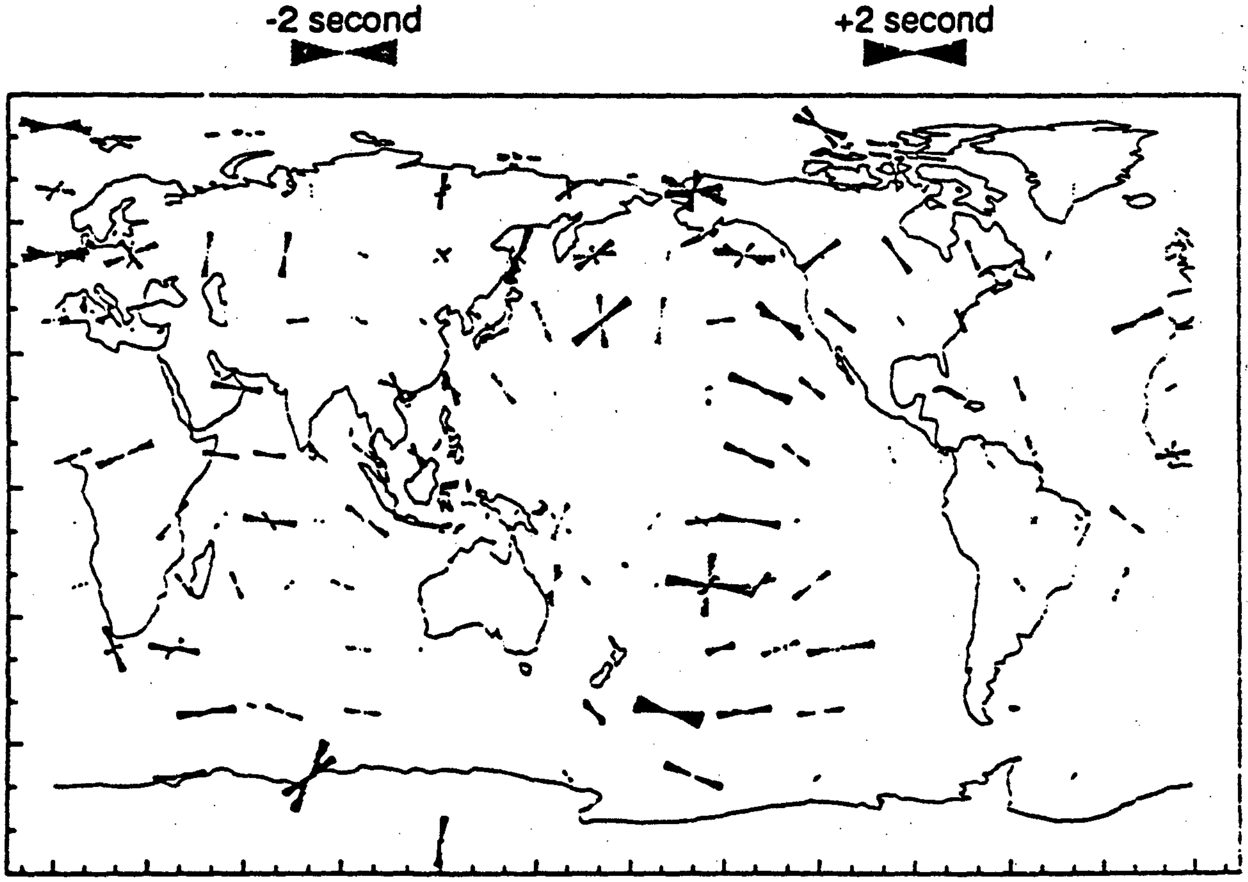

**Figure 13.**

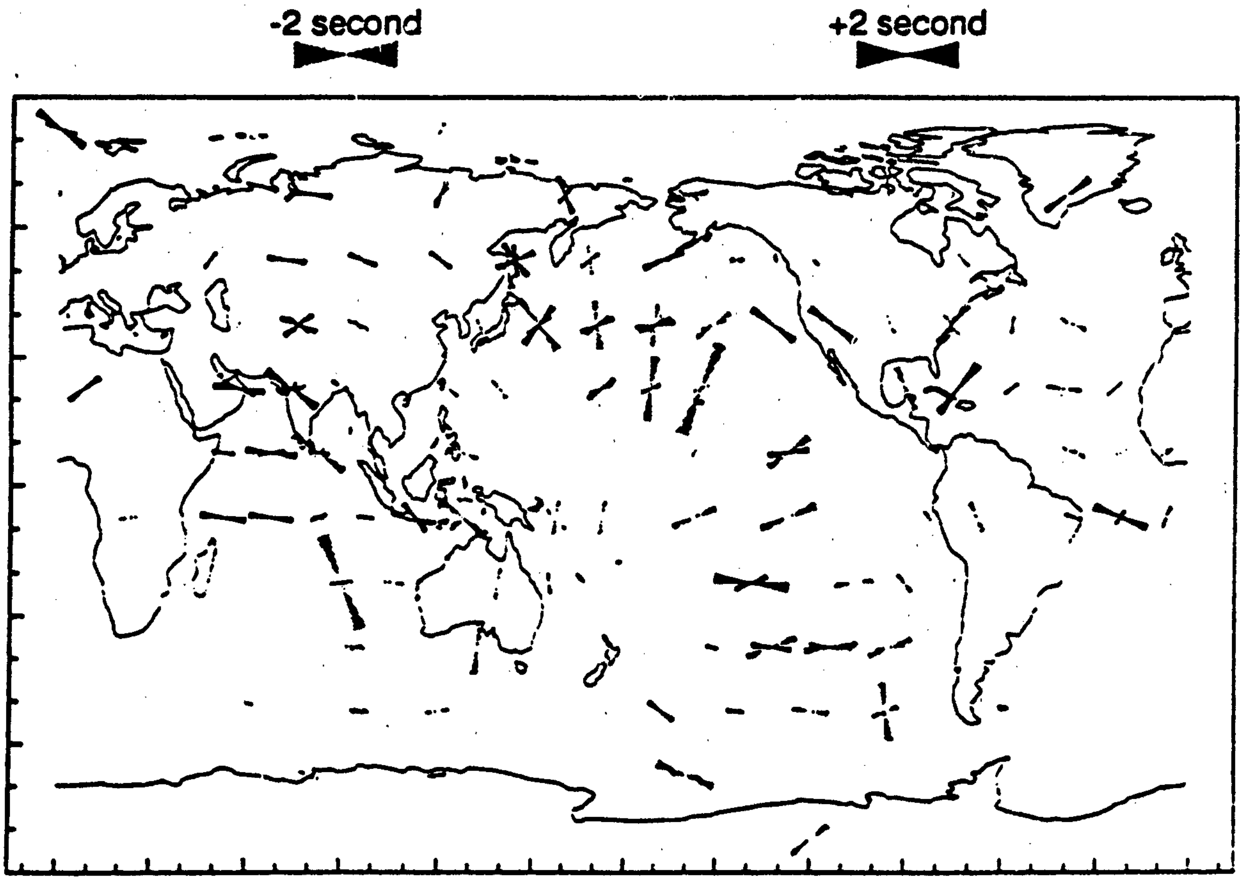

Figure 14.

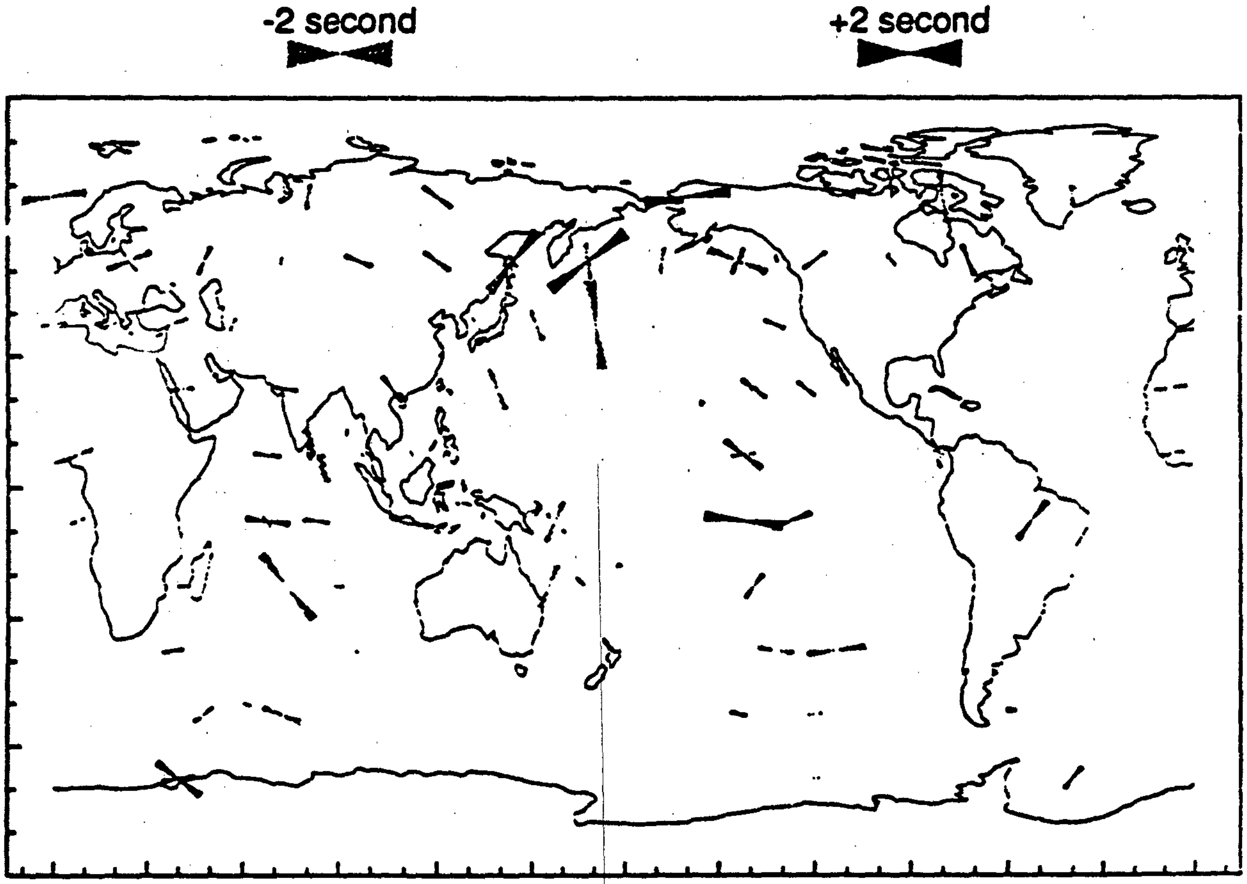

Figure 15.

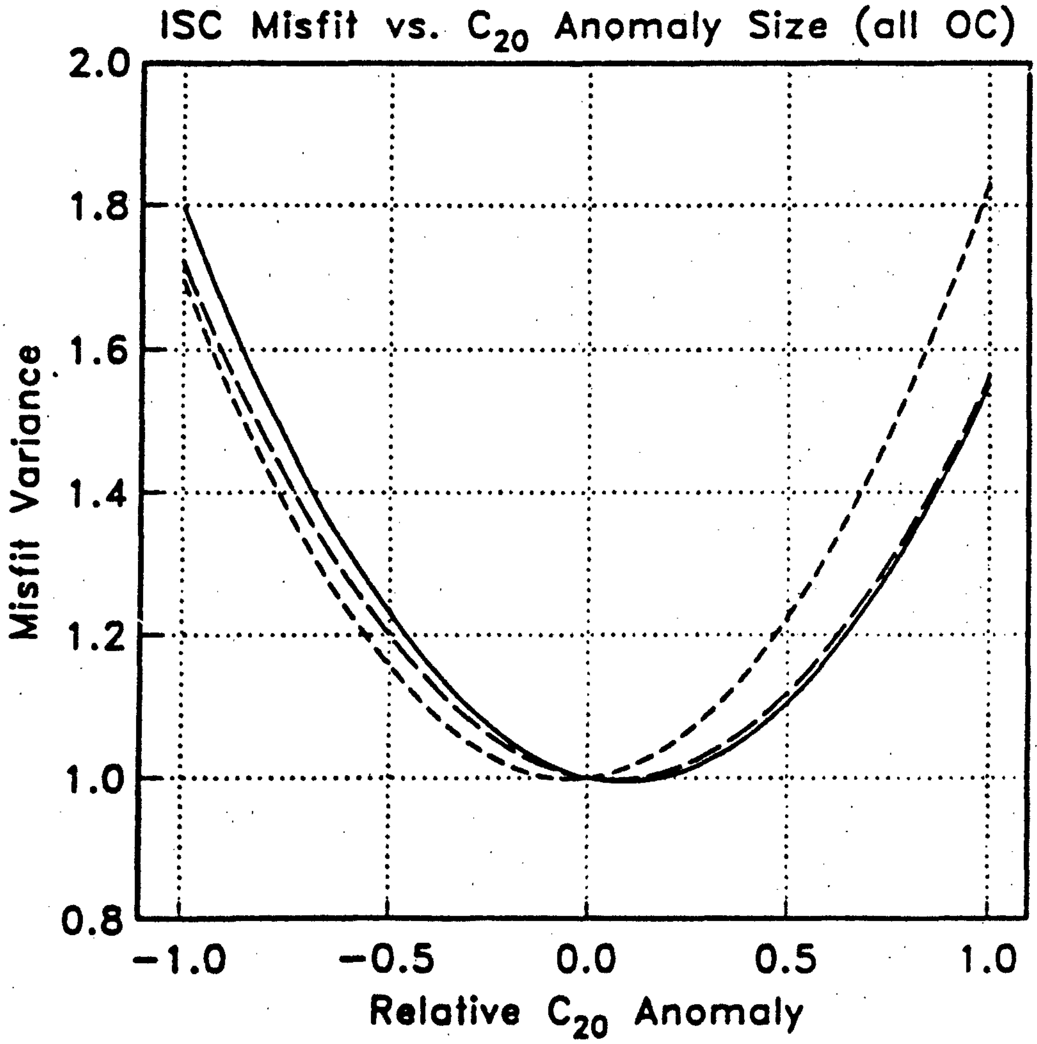
ISC Misfit vs. $C_{20}$ Anomaly Size (all OC)
Misfit Variance
2.0
1.8
1.6
1.4
1.2
1.0
0.8
−1.0
−0.5
0.0
0.5
1.0
Relative $C_{20}$ Anomaly

**Figure 16.**

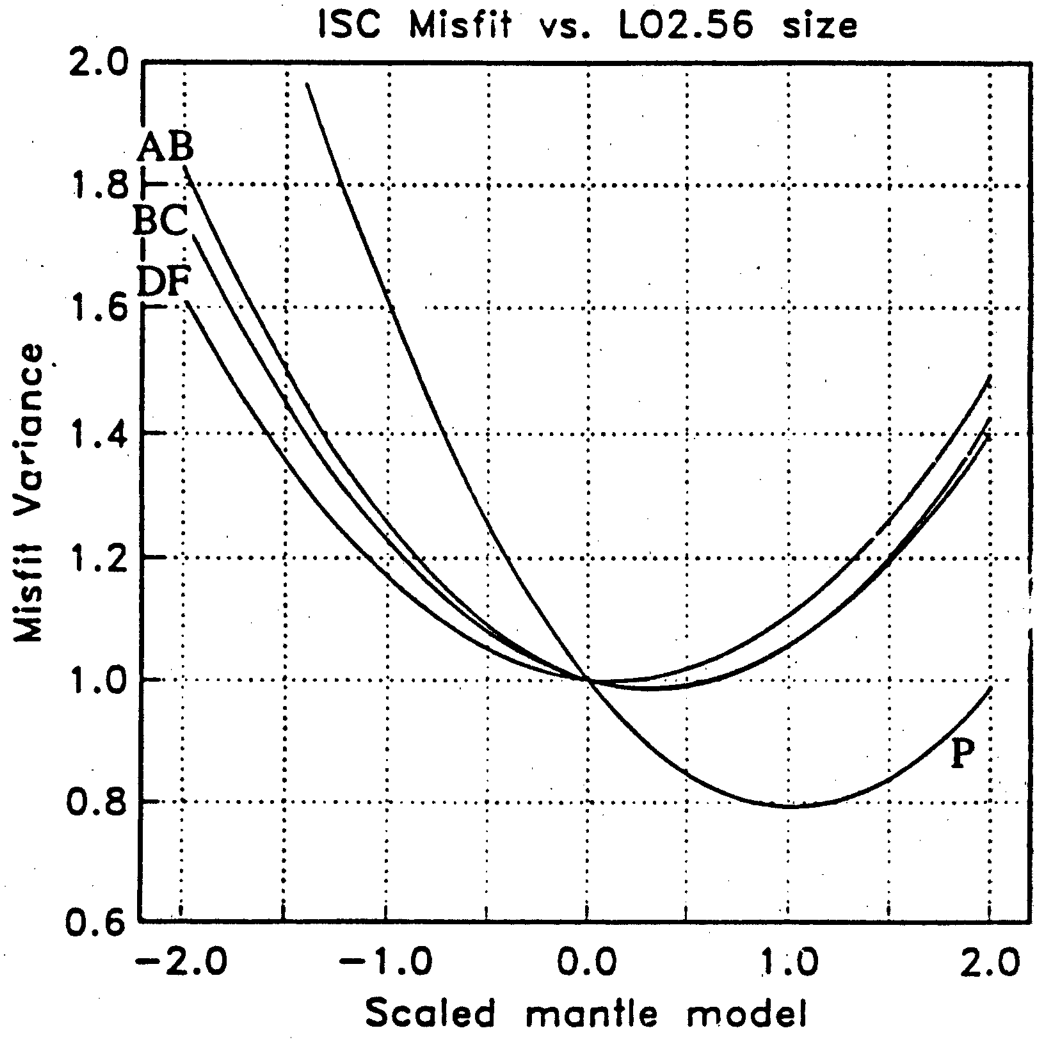
ISC Misfit vs. L02.56 size
Misfit Variance
Scaled mantle model
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
−2.0
−1.0
0.0
1.0
2.0
AB
BC
DF
P

Figure 17.

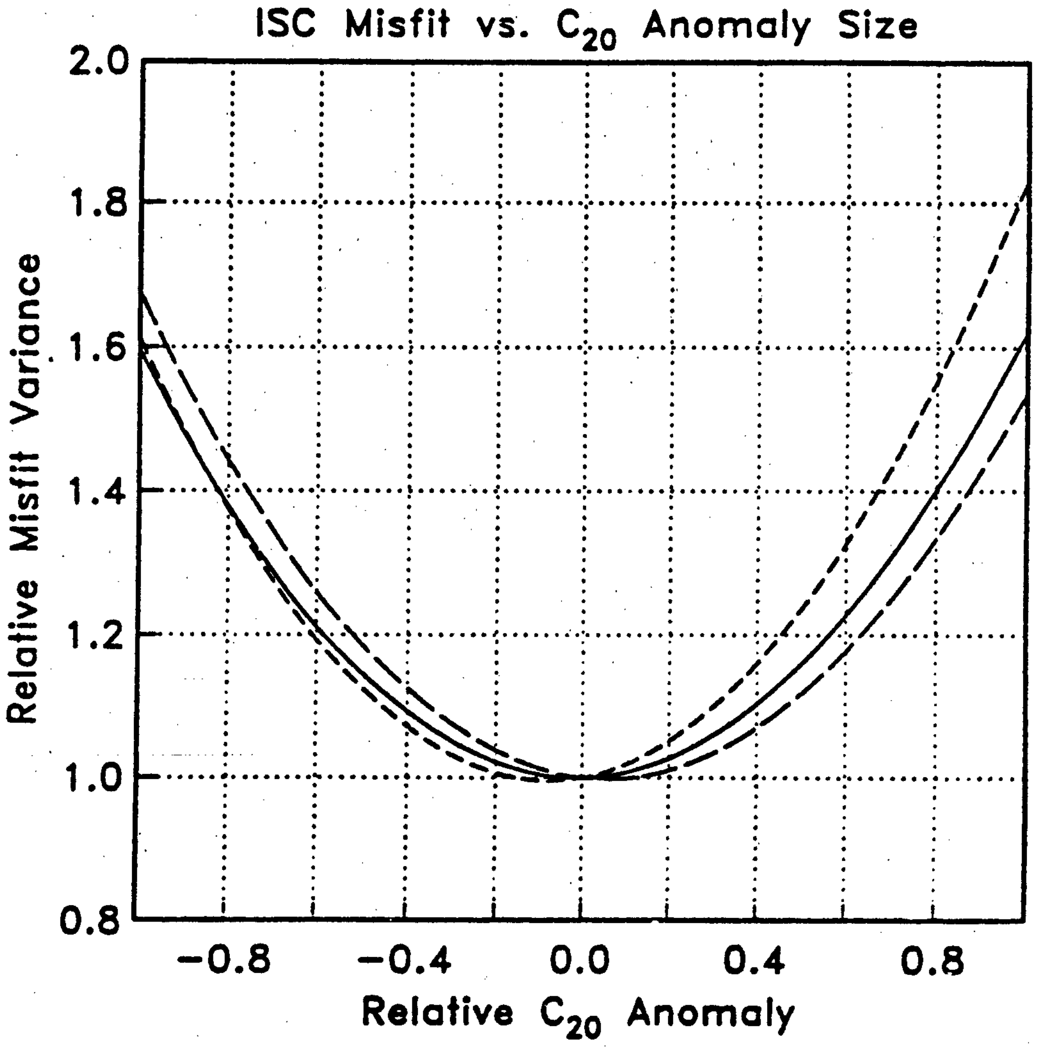
ISC Misfit vs. C20 Anomaly Size
Relative Misfit Variance
2.0
1.8
1.6
1.4
1.2
1.0
0.8
−0.8
−0.4
0.0
0.4
0.8
Relative C20 Anomaly

**Figure 18**

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