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GEO-GEO CROSS-CALIBRATION RESULTS FOR AE9 DEVELOPMENT

Wm. Robert Johnston

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Technical Report

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14. ABSTRACT
This report summarizes cross calibration of energetic electron observations between pairs of LANL geosynchronous (GEO) satellites. Of the GEO satellites considered, seven carried Synchronous Orbit Particle Analyzer (SOPA) detectors and two carried the Charged Particle Analyzer (CPA) detector. Discussion covers the comparison method used, information on available data and results for cross calibration offsets and residual errors. These cross calibrations were performed as part of overall intercalibration efforts for development of the AE9 radiation belt model.

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1. INTRODUCTION

This document summarizes cross calibration of energetic electron observations between pairs of LANL geosynchronous (GEO) satellites. Of the GEO satellites considered, seven carried Synchronous Orbit Particle Analyzer (SOPA) detectors (LANL 1989-046, LANL 1990-095, LANL 1991-080, LANL 1994-084, LANL-97A, LANL-01A, and LANL-02A) and two carried the Charged Particle Analyzer (CPA) detector (LANL 1984-129 and 1987-097). Discussion covers the comparison method used, information on available data and results for cross calibration offsets and residual errors. These cross calibrations were performed as part of overall intercalibration efforts for development of the AE9 radiation belt model.

2. BACKGROUND

The AE9/AP9/SPM model is a set of climatological models specifying the trapped radiation and plasma environment in near-Earth space [1]. Its novel features include quantitative estimates of uncertainty from both measurement uncertainty and environmental variability. The flux maps are statistically merged from multiple data sets which must be cross-calibrated for two reasons: to identify and eliminate systematic biases in each data set relative to an adopted standard instrument, and to quantify observational uncertainty for each data set.

Cross-calibration of electron data sets is based on comparison of on-orbit observations by a pair of satellites of a similar environment during spatial-temporal conjunctions. This approach is based on that of [2]. The adopted standard instruments for electron data sets are those from the Medium Energy A (MEA) and High Energy Electron Fluxmeter (HEEF) instruments on the Combined Radiation and Release Experiment (CRRES) mission. These CRRES data sets were cross-calibrated with two LANL GEO data sets (1989-046 and 1990-095), providing a cross-calibration link between the CRRES standard and the other GEO satellites covered here.

This document reviews cross calibration between various pairings of LANL GEO satellites. Data are available from seven Synchronous Orbit Particle Analyzer (SOPA) detectors, those on LANL 1989-046, LANL 1990-095, LANL 1991-080, LANL 1994-084, LANL-97A, LANL-01A, and LANL-02A. Several of these SOPA data sets were used directly in AE9. Data are also available from two Charged Particle Analyzer (CPA) detectors, those on 1984-129 and 1987-097. As the CPA is a less sophisticated instrument than the SOPA, these data sets were not directly used in AE9, but the cross-calibration was needed to provide a calibration chain to other data sets (as dictated by time and orbit location of the respective data sets).

3. METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Data Used

The LANL GEO data used is spin-averaged omnidirectional SOPA data from satellites 1989-046 and 1990-095. The SOPA instrument has 10 electron energy channels in the range 0.05-1.6 MeV. LANL has processed this data by fitting the channel fluxes with the sum of two relativistic Maxwellians [3, 4]. The data files we are using include, at 10 sec intervals: satellite ephemeris (time and GEO position), density and temperature parameters for the bi-relativistic

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Maxwellian fit; estimated counts based on these fits for the 10 channels (50-75 keV, 75-105 keV, 105-150 keV, 150-225 keV, 225-315 keV, 315-500 keV, 500-750 keV, 0.75-1.1 MeV, 1.1-1.5 MeV, and >1.5 MeV), and the omnidirectional fluxes from the fit spectra evaluated at 16 energies from 24.1 keV to 4 MeV. For the cross calibration analysis we used the channel values (0.05-1.5 MeV), which are from LANL's inversion of the SOPA data using SOPA response functions and assuming the bi-modal spectra [5].

Available data is of three types, here designated types A, B, and C:

A. Spin-averaged data for both SOPA and CPA, 10-sec cadence (filenames yymmdd_sat.txt)
B. Spin-averaged data for SOPA, 10-sec cadence—these were used for the CRRES-GEO cross calibration. (filenames yyymmdd_sat_l2-001.txt)
C. Directional data for SOPA, cdf files, 5-min cadence—we have concentrated on these since this is the data to be used in AE9. (filenames LANL_sat_H3_SOPA_yyyymmdd_V01.cdf)

Table 1 gives number of days of data in hand for each satellite and each data type at the time of analysis.

Table 1: GEO satellite data available

Satellite	instrument	days, A data	days, B data	days, C data
1984-129	CPA	304		
1987-097	CPA	312		
1989-046	SOPA	364	3298	97
1990-095	SOPA	343	4528	725
1991-080	SOPA	308	3920	1
1994-084	SOPA		4176	
LANL-97A	SOPA		3296	1867
LANL-01A	SOPA		2380	5
LANL-02A	SOPA		2011	1389

The omnidirectional type C data is preferred for AE9, so main results are provided from this data. Cross calibration results from type B data have been obtained, partly as a check on the calibrations from type C data and partly to enable use of additional satellites as needed.

3.2 Comparison Method Used

Since GEO satellites generally do not undergo conjunctions, but are in circular orbits near the magnetic equator (and consequently have limited range in L* and B/B_0), we compare daily averages of flux observations. This incidentally eliminates the need for ephemeris information. We did find that Kp-based restrictions did improve results (i.e. reducing variability) as long as sufficient days of overlapping data were available. Results are presented for analyses limited to days with Kp<2 (last 2 days) and for no Kp restriction. Results are with respect to satellites 1989-046 and/or 1990-095, since these are the satellites calibrated to CRRES [6]. Table 2 gives days of data for satellite pairs.

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Table 2: Days of available overlapping data for satellite pairs

	1989-046			1990-095		
	C, Kp<2	C, all Kp	B, Kp<2	C, Kp<2	C, all Kp	B, Kp<2
1991-080			89			242
1994-084			171			228
LANL-97A	22	96	152	14	710	146
LANL-01A			134		5	94
LANL-02A	23	96	125	8	585	82

3.3 Statistics Derived

Calculated statistics include statistics on the ratio of fluxes observed by the two satellites, the correlation coefficients, and the residual error. If $\mathbf{J}_A$ and $\mathbf{J_B}$ are the series of flux observations from comparable channels on two satellites A and B, respectively, while they meet conjunction criteria, the median ratio is

$$R=\text{median}(\mathbf{J}_B/\mathbf{J}_A). \quad (1)$$

This is the notional ratio by which the two satellites disagree, and it can be used to obtain an adjusted flux series for satellite B,

$$\mathbf{J'}_B=\mathbf{J}_B/R, \quad (2)$$

so that the series $\mathbf{J}_A$ and $\mathbf{J'}_B$ have the same medians. We express residual error as the natural log of the ratios of these series $\mathbf{J}_A$ and $\mathbf{J'}_A$, or as the series

$$\mathbf{RE}=\ln(\mathbf{J'}_B/\mathbf{J}_A). \quad (3)$$

Among statistics regarding this series is the root mean squared error (RMSE):

$$RMSE=[(1/n)(\Sigma\ \mathbf{RE}^2)]^{0.5}. \quad (4)$$

These are essentially the bias (=ln R) and dlnj (=RMSE) used in the AE9/AP9/SPM Technical Documentation.

4. RESULTS AND DISCUSSION

4.1 Results, GEO/SOPA Pairings

For a given choice of data and energy channel, the daily average fluxes observed by each of a pair of GEO satellites formed a set of data points for calibration statistics.

Tables 3-7 give the results for the satellite pairings, for each energy channel reported in the SOPA data, as the following:

- mean ratio (of GEO2 flux to GEO1 flux);
- median ratio in bold bracketed by high and low values representing 95% of the range of ratios (i.e. this column gives the 2.5th, the 50th, and the 97.5th percentiles of the ratios);
- the correlation coefficient (CC) statistic; and
- for the residual error, the median of the magnitude (medRE) and the root mean squared error (RMSE). These are given for comparisons to 1989-046 and to 1990-095.

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Appendix A provides figures showing the cross-calibration results for LANL-97A, LANL-02A, 1991-080, 1994-084, and LANL-01A:

- scatter plots by channel of GEO2 flux vs. GEO1 flux;
- the channel flux ratios as functions of energy; and
- histograms of the natural log of flux ratios (same as residual error histograms without adjustment of the median to zero).

Note that only comparisons for LANL-97A and LANL-02A are presented from type C data; for the remaining satellites, insufficient type C data were available so results are given from type B data. The reported energy channels in the two datasets vary slightly.

Table 3: Cross calibration results for LANL-97A

Conj list	Type C, all Kp, from 1989-046					Type C, all Kp, from 1990-095				
E (MeV)	mean	median & 95% range	CC	medRE	RMSE	mean	median & 95% range	CC	medRE	RMSE
0.050	0.679	0.359 **0.688** 1.129	0.986	0.266	**0.315**	0.689	0.257 **0.676** 2.154	0.771	0.295	**0.531**
0.075	0.685	0.442 **0.683** 1.034	0.984	0.210	**0.248**	0.758	0.347 **0.741** 1.948	0.800	0.227	**0.451**
0.105	0.699	0.475 **0.706** 1.020	0.981	0.155	**0.187**	0.858	0.447 **0.845** 2.038	0.818	0.184	**0.398**
0.150	0.735	0.511 **0.740** 0.976	0.976	0.065	**0.146**	1.036	0.536 **1.043** 2.432	0.808	0.167	**0.387**
0.225	0.826	0.559 **0.848** 0.999	0.969	0.065	**0.151**	1.268	0.526 **1.305** 2.750	0.769	0.184	**0.413**
0.315	0.886	0.574 **0.899** 1.261	0.959	0.051	**0.145**	1.228	0.534 **1.271** 2.472	0.805	0.166	**0.394**
0.500	0.865	0.534 **0.876** 1.159	0.968	0.054	**0.165**	1.108	0.462 **1.136** 2.658	0.851	0.196	**0.447**
0.750	0.833	0.511 **0.884** 1.040	0.977	0.063	**0.240**	1.013	0.328 **1.050** 3.002	0.857	0.271	**0.618**
1.100	0.792	0.327 **0.866** 1.142	0.984	0.139	**0.383**	0.871	0.191 **0.911** 3.775	0.847	0.444	**0.908**
1.500	0.751	0.267 **0.888** 1.240	0.985	0.195	**0.573**	0.716	0.100 **0.756** 5.721	0.833	0.608	**1.267**

Table 4: Cross calibration results for LANL-02A

Conj list	Type C, all Kp, from 1989-046					Type C, all Kp, from 1990-095				
E (MeV)	mean	median & 95% range	CC	medRE	RMSE	mean	median & 95% range	CC	medRE	RMSE
0.050	0.863	0.466 **0.845** 1.721	0.931	0.152	**0.335**	0.741	0.367 **0.713** 2.032	0.840	0.231	**0.436**
0.075	0.932	0.599 **0.917** 1.651	0.948	0.124	**0.263**	0.884	0.486 **0.864** 2.000	0.865	0.189	**0.364**
0.105	1.015	0.691 **1.008** 1.658	0.964	0.082	**0.205**	1.081	0.640 **1.069** 2.106	0.883	0.159	**0.311**
0.150	1.120	0.696 **1.121** 1.545	0.973	0.069	**0.177**	1.399	0.814 **1.405** 2.541	0.881	0.150	**0.292**
0.225	1.125	0.581 **1.179** 1.532	0.969	0.046	**0.217**	1.626	0.798 **1.677** 2.945	0.850	0.176	**0.320**
0.315	0.953	0.490 **0.980** 1.319	0.972	0.079	**0.212**	1.309	0.631 **1.354** 2.362	0.862	0.157	**0.314**
0.500	0.918	0.538 **0.920** 1.309	0.977	0.076	**0.193**	1.175	0.589 **1.186** 2.169	0.892	0.152	**0.338**
0.750	1.029	0.656 **1.030** 1.601	0.981	0.075	**0.203**	1.256	0.504 **1.257** 2.974	0.901	0.212	**0.443**
1.100	1.194	0.671 **1.215** 2.310	0.979	0.077	**0.256**	1.337	0.395 **1.302** 4.592	0.899	0.296	**0.626**
1.500	1.384	0.534 **1.452** 2.942	0.974	0.133	**0.344**	1.390	0.278 **1.336** 8.599	0.891	0.414	**0.854**

Table 5: Cross calibration results for 1991-080

Conj list	Type B, Kp<2, from 1989-046					Type B, Kp<2, from 1990-095				
E (MeV)	mean	median & 95% range	CC	medRE	RMSE	mean	median & 95% range	CC	medRE	RMSE
0.0625	0.848	0.020 **0.962** 10.979	0.544	0.118	**1.194**	1.125	0.284 **1.158** 8.107	0.361	0.147	**0.900**
0.090	0.846	0.009 **0.963** 6.369	0.588	0.112	**1.061**	1.092	0.283 **1.106** 7.444	0.407	0.129	**0.832**
0.1275	0.690	0.026 **0.810** 2.068	0.649	0.098	**0.912**	1.044	0.284 **1.064** 5.102	0.514	0.150	**0.747**
0.1875	0.661	0.208 **0.791** 1.061	0.622	0.097	**0.800**	1.079	0.358 **1.061** 2.792	0.634	0.149	**0.565**
0.270	0.688	0.224 **0.802** 1.136	0.744	0.105	**0.722**	1.068	0.526 **1.036** 3.469	0.791	0.158	**0.547**
0.4075	0.539	0.138 **0.621** 0.998	0.851	0.118	**0.565**	1.077	0.532 **1.048** 3.711	0.829	0.163	**0.557**
0.625	0.682	0.165 **0.751** 1.438	0.934	0.145	**0.446**	1.085	0.423 **1.052** 4.210	0.817	0.192	**0.669**
0.925	0.700	0.275 **0.744** 1.606	0.943	0.197	**0.441**	1.042	0.458 **0.999** 4.508	0.886	0.222	**0.602**
1.30	0.777	0.324 **0.756** 1.631	0.930	0.268	**0.468**	0.992	0.454 **0.979** 2.863	0.902	0.151	**0.462**
2.00	1.029	0.632 **1.018** 1.499	0.868	0.189	**0.249**	0.965	0.650 **0.999** 1.130	0.884	0.014	**0.178**

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Table 6: Cross calibration results for 1994-084

Conj list	Type B, Kp<2, from 1989-046					Type B, Kp<2, from 1990-095				
E (MeV)	mean	median & 95% range	CC	medRE	RMSE	mean	median & 95% range	CC	medRE	RMSE
0.0625	0.908	0.392 **0.844** 7.111	0.431	0.121	**0.897**	0.988	0.443 **0.971** 3.287	0.583	0.139	**0.623**
0.090	1.093	0.553 **1.012** 6.838	0.455	0.111	**0.905**	1.147	0.510 **1.130** 3.318	0.648	0.134	**0.589**
0.1275	0.834	0.468 **0.777** 4.232	0.547	0.107	**0.858**	0.999	0.480 **0.969** 2.561	0.740	0.137	**0.529**
0.1875	0.795	0.458 **0.764** 3.590	0.608	0.117	**0.787**	1.020	0.500 **1.000** 2.603	0.741	0.134	**0.526**
0.270	0.744	0.440 **0.704** 3.760	0.781	0.160	**0.718**	0.897	0.407 **0.859** 2.069	0.834	0.152	**0.507**
0.4075	0.806	0.458 **0.760** 1.777	0.858	0.149	**0.617**	1.291	0.621 **1.236** 3.081	0.856	0.170	**0.526**
0.625	0.803	0.414 **0.763** 1.452	0.939	0.155	**0.454**	1.062	0.511 **1.005** 3.069	0.841	0.214	**0.648**
0.925	0.779	0.428 **0.737** 1.277	0.973	0.169	**0.343**	0.976	0.474 **0.925** 2.605	0.921	0.286	**0.545**
1.30	0.809	0.439 **0.763** 1.380	0.976	0.181	**0.303**	0.885	0.497 **0.801** 2.204	0.950	0.261	**0.422**
2.00	0.487	0.352 **0.435** 1.160	0.972	0.178	**0.358**	0.369	0.243 **0.332** 0.970	0.723	0.283	**0.421**

Table 7: Cross calibration results for LANL-01A

Conj list	Type B, Kp<2, from 1989-046					Type B, Kp<2, from 1990-095				
E (MeV)	mean	median & 95% range	CC	medRE	RMSE	mean	median & 95% range	CC	medRE	RMSE
0.0625	1.398	0.542 **1.257** 13.965	0.271	0.085	**1.134**	1.297	0.681 **1.376** 1.932	0.271	0.083	**0.921**
0.090	1.191	0.634 **1.068** 13.784	0.326	0.073	**1.063**	1.099	0.634 **1.157** 1.594	0.321	0.073	**0.880**
0.1275	1.075	0.634 **0.978** 13.021	0.464	0.063	**0.941**	1.150	0.737 **1.182** 1.597	0.454	0.075	**0.820**
0.1875	0.982	0.574 **0.936** 7.798	0.650	0.058	**0.672**	1.186	0.739 **1.181** 1.601	0.599	0.072	**0.695**
0.270	0.954	0.632 **0.926** 1.605	0.930	0.040	**0.366**	1.110	0.647 **1.070** 1.638	0.760	0.078	**0.653**
0.4075	0.961	0.710 **0.960** 1.545	0.990	0.067	**0.149**	1.461	0.898 **1.421** 2.136	0.817	0.095	**0.574**
0.625	1.047	0.767 **1.057** 1.320	0.993	0.065	**0.134**	1.207	0.577 **1.195** 2.155	0.904	0.108	**0.459**
0.925	1.168	0.736 **1.193** 1.598	0.994	0.055	**0.161**	1.209	0.420 **1.227** 2.501	0.958	0.134	**0.377**
1.30	1.157	0.703 **1.182** 1.542	0.992	0.063	**0.189**	1.142	0.573 **1.162** 2.097	0.971	0.177	**0.323**
2.00	0.652	0.363 **0.648** 1.262	0.976	0.368	**0.403**	0.559	0.350 **0.496** 0.968	0.971	0.117	**0.318**

4.2 Check of Results, GEO/SOPA to CRRES

Recall that the notional calibration sequence is from CRRES to an overlapping GEO satellite GEO1 (either 1989-046 or 1990-095), then from GEO1 to a secondary GEO satellite GEO2. As a general comparison of results, notional adjustment factors are obtained by taking the product of the median (GEO1/CRRES) flux ratios and the median (GEO2/GEO1) flux ratios, yielding median (GEO2/CRRES) flux ratios. To test consistency, results are presented in Tables 8-9 for the six combinations of GEO1 and data set (i.e. columns of Table 2), for both GEO2 satellites where all six comparisons are possible (LANL-97A and LANL-02A. Note that CRRES-GEO1 comparisons are only possible for 0.128-1.3 MeV channels.

Results are more consistent below ~0.5 MeV. These results can also be used to obtain LANL-02A/LANL-97A ratios, and compared to ratios derived by directly comparing these satellites. Such a test shows significant scatter using type C data with the Kp restriction. Given that this restriction makes little difference in the above results it will not be used for the unidirectional comparisons.

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Table 8: Comparisons of LANL-97A to 1989-046 and 1990-095

LANL-97A	1989-046			1990-095		
E (MeV)	C, Kp<2	C, all Kp	B, Kp<2	C, Kp<2	C, all Kp	B, Kp<2
0.050	0.219	0.296	0.322	0.182	0.207	0.267
0.075	0.240	0.294	0.338	0.215	0.227	0.279
0.105	0.259	0.303	0.231	0.262	0.258	0.219
0.150	0.374	0.376	0.306	0.424	0.362	0.281
0.225	0.442	0.439	0.362	0.581	0.515	0.334
0.315	0.439	0.406	0.313	0.612	0.506	0.416
0.500	0.728	0.716	0.611	1.066	0.860	0.664
0.750	0.969	0.995	0.804	1.800	1.464	1.160
1.100	0.924	0.908	0.903	2.173	1.576	1.644
1.500	0.848	0.813	0.409	1.879	1.312	0.740

Table 9: Comparisons of LANL-02A to 1989-046 and 1990-095

LANL-02A	1989-046			1990-095		
E (MeV)	C, Kp<2	C, all Kp	B, Kp<2	C, Kp<2	C, all Kp	B, Kp<2
0.050	0.356	0.363	0.425	0.209	0.218	0.322
0.075	0.392	0.394	0.478	0.252	0.264	0.360
0.105	0.436	0.434	0.436	0.315	0.327	0.381
0.150	0.595	0.569	0.497	0.486	0.488	0.430
0.225	0.597	0.611	0.439	0.659	0.662	0.367
0.315	0.467	0.443	0.332	0.582	0.538	0.426
0.500	0.755	0.753	0.754	0.953	0.898	0.824
0.750	1.103	1.160	1.390	2.014	1.754	2.026
1.100	1.224	1.274	1.628	2.533	2.251	3.139
1.500	1.329	1.328	0.864	2.674	2.320	1.443

4.3 Check of Results, GEO/SOPA 1989-046 to 1990-095

Satellites 1989-046 and 1990-095 were each cross-calibrated with CRRES. This section describes direct cross-calibration between these two GEO satellites. Of data types discussed in this report, we have type B data (spin-averaged) but not type C data (omnidirectional) for overlapping periods for 1989-046 and 1990-095. The following results thus are from type B data, spin-averaged 10-sec cadence SOPA data, of which there are 1997 days of overlapping data for 1989-046 and 1990-095, but only 96 days meeting the requirement that Kp<2 for the last 48 hrs. Cross calibration results for both cases are given in Table 10.

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Table 10: Cross calibration results for 1990-095 vs. 1989-046

Conj list	Type B, Kp<2					Type B, all Kp				
E (MeV)	mean	median & 95% range	CC	medRE	RMSE	mean	median & 95% range	CC	medRE	RMSE
0.0625	0.898	0.130 **0.878** 8.781	0.310	0.202	**1.142**	0.780	0.179 **0.795** 2.870	0.601	0.284	**0.874**
0.090	0.921	0.103 **0.943** 9.186	0.335	0.171	**1.055**	0.829	0.228 **0.843** 2.614	0.629	0.237	**0.821**
0.1275	0.794	0.057 **0.823** 7.289	0.425	0.183	**0.927**	0.761	0.233 **0.783** 2.147	0.669	0.193	**0.766**
0.1875	0.731	0.150 **0.796** 2.302	0.609	0.168	**0.630**	0.743	0.245 **0.768** 1.772	0.719	0.190	**0.677**
0.270	0.751	0.152 **0.854** 1.335	0.761	0.180	**0.615**	0.840	0.260 **0.884** 1.894	0.781	0.172	**0.636**
0.4075	0.576	0.105 **0.643** 1.133	0.791	0.179	**0.640**	0.672	0.185 **0.719** 1.390	0.850	0.196	**0.577**
0.625	0.746	0.194 **0.796** 1.744	0.854	0.195	**0.598**	0.861	0.207 **0.939** 2.047	0.888	0.239	**0.677**
0.925	0.789	0.156 **0.875** 1.720	0.883	0.289	**0.625**	0.867	0.169 **0.968** 2.162	0.906	0.298	**0.710**
1.30	0.916	0.164 **1.009** 1.756	0.878	0.285	**0.576**	0.880	0.200 **0.950** 2.123	0.912	0.319	**0.651**
>1.50	1.107	0.622 **1.180** 1.500	0.821	0.156	**0.280**	0.949	0.454 **1.003** 1.663	0.824	0.236	**0.424**

Table 11 gives the median channel flux ratios for 1990-095 relative to 1989-046 from both cross calibrations for 7 channel energies (first column). The second column gives ratios derived from the calibration of each satellite against CRRES. The third and fourth columns give ratios from the calibration of the two GEO satellites with each other using restrictions on Kp or using no Kp restrictions, respectively. Note that the CRRES-based comparisons are from conjunctions while the GEO-GEO comparisons are from daily averages.

Table 11: Comparison of 1989-046 and 1990-095 cross-calibration results for median ratios

E (MeV)	median ratio, from CRRES-GEO, conj., V3	median ratio, direct GEO-GEO, type B daily data, Kp<2 last 48 hr	median ratio, direct GEO-GEO, type B daily data, all Kp
0.1275	**0.712**	**0.823**	**0.783**
0.1875	**0.654**	**0.796**	**0.768**
0.270	**0.984**	**0.854**	**0.884**
0.4075	**0.751**	**0.643**	**0.719**
0.625	**1.057**	**0.796**	**0.939**
0.925	**1.479**	**0.875**	**0.968**
1.30	**1.897**	**1.009**	**0.950**

Figure 1 below shows the 1990-095-to-1989-046 channel ratios: red line is that derived from the respective comparisons to CRRES (ratios from V3 results, given in Table 11); black is from the direct comparison, with thin black lines indicating 2.5th and 97.5th percentiles (Kp<2 last 48 hr); blue lines are the 96 daily comparisons (direct GEO-GEO).

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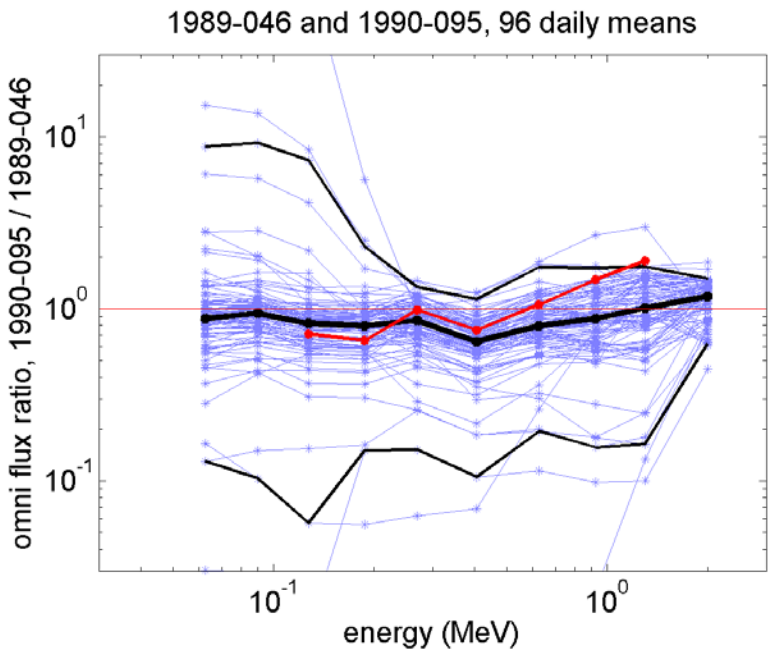

Figure 1: Omnidirectional flux ratios vs. channel energy, 1990-095 vs. 1989-046

The final figures show the cross-calibration results for 1990-095 vs. 1989-046: scatter plots by channel of GEO2 flux vs. GEO1 flux; channel flux ratios as functions of energy; and histograms of the natural log of flux ratios (same as residual error histograms without adjustment of the median to zero).

4.4 Results, GEO/SOPA to GEO 1984-129/CPA

This section summarizes cross calibration of GEO 1984-129 CPA with CRRES MEA and with GEO SOPAs, with the objective of providing a calibration linkage to the SCATHA/SC3.

Cross calibration of 1984-129 with GEO SOPAs, as with previous GEO-GEO cross calibrations, used daily averages of data. Data from 1984-129 CPA was interpolated to the LANL SOPA channel energies. Results are presented from comparing daily average observations with the restriction to days with Kp<3 for the last 48 hours.

Table 12: Results for 1984-129 relative to 1989-046 (57 days)

E (MeV)	mean	2.50%	**median**	97.50%	cc	medRE	**RMSE**
0.0625	6.861	2.938	**7.231**	14.635	0.554	0.145	**0.801**
0.0900	3.843	2.032	**4.170**	6.475	0.631	0.136	**0.662**
0.1275	3.065	1.961	**3.323**	4.242	0.774	0.117	**0.458**
0.1875	1.841	1.076	**1.949**	2.494	0.908	0.133	**0.259**
0.2700	3.024	2.022	**3.140**	3.854	0.968	0.107	**0.181**
0.4075	1.947	1.178	**2.094**	2.751	0.971	0.125	**0.227**
0.6250	1.140	0.587	**1.190**	1.691	0.969	0.151	**0.248**
0.9250	1.160	0.565	**1.220**	1.726	0.970	0.114	**0.247**
1.3000	1.789	0.833	**1.866**	2.941	0.957	0.194	**0.311**

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Table 13: Results for 1984-129 relative to 1990-095 (42 days)

E (MeV)	mean	2.50%	**median**	97.50%	cc	medRE	**RMSE**
0.0625	6.412	0.477	**8.725**	20.106	0.312	0.219	**1.257**
0.0900	3.473	0.294	**4.797**	8.792	0.351	0.178	**1.157**
0.1275	3.151	0.406	**4.113**	7.279	0.434	0.221	**0.976**
0.1875	2.263	0.830	**2.475**	3.906	0.687	0.258	**0.507**
0.2700	3.733	2.070	**3.685**	6.347	0.901	0.178	**0.302**
0.4075	3.136	1.382	**3.147**	5.959	0.903	0.207	**0.344**
0.6250	1.413	0.638	**1.345**	2.969	0.915	0.219	**0.380**
0.9250	1.334	0.775	**1.253**	3.067	0.948	0.209	**0.364**
1.3000	1.910	1.181	**1.793**	3.749	0.959	0.255	**0.360**

Table 14: Results for 1984-129 relative to 1991-080 (41 days)

E (MeV)	mean	2.50%	**median**	97.50%	cc	medRE	**RMSE**
0.0625	6.109	0.268	**7.820**	15.079	0.604	0.229	**1.047**
0.0900	3.509	0.275	**4.417**	7.678	0.687	0.205	**0.829**
0.1275	3.610	0.743	**3.978**	7.573	0.775	0.174	**0.537**
0.1875	2.528	1.299	**2.584**	4.724	0.880	0.158	**0.323**
0.2700	4.160	2.471	**4.060**	7.887	0.907	0.174	**0.335**
0.4075	3.571	1.718	**3.463**	7.983	0.900	0.234	**0.402**
0.6250	1.757	0.741	**1.725**	7.264	0.858	0.253	**0.531**
0.9250	1.734	0.694	**1.737**	7.769	0.855	0.246	**0.572**
1.3000	2.637	1.101	**2.917**	4.204	0.911	0.227	**0.439**

No days with data are available for 1984-129 relative to: 1994-084, LANL-97A, LANL-01A.

4.5 Check of Results, GEO 1984-129/CPA to CRRES

Table 15 compares results for GEO 1984-129 CPA relative to CRRES, either directly or via the calibrations against GEO 1989-046 and GEO 1990-095 SOPAs. 1984-129/CRRES results are interpolated to the energies used for the GEO-GEO cross-calibration.

Table 15: Median bias, results chained back to CRRES from GEO 1984-129.

E (MeV)	Median, direct	Median, via 1989-046	Median, via 1990-095
0.128	0.453	1.429	1.259
0.188	0.427	1.243	1.032
0.270	0.398	1.174	1.356
0.408	0.452	1.279	1.444
0.625	0.372	1.305	1.560
0.925	0.459	1.423	2.160
1.300	1.142	1.707	3.113

Figure 2 below compares direct and indirect cross calibration results, 1984-129 CPA and CRRES MEA, using results from [6].

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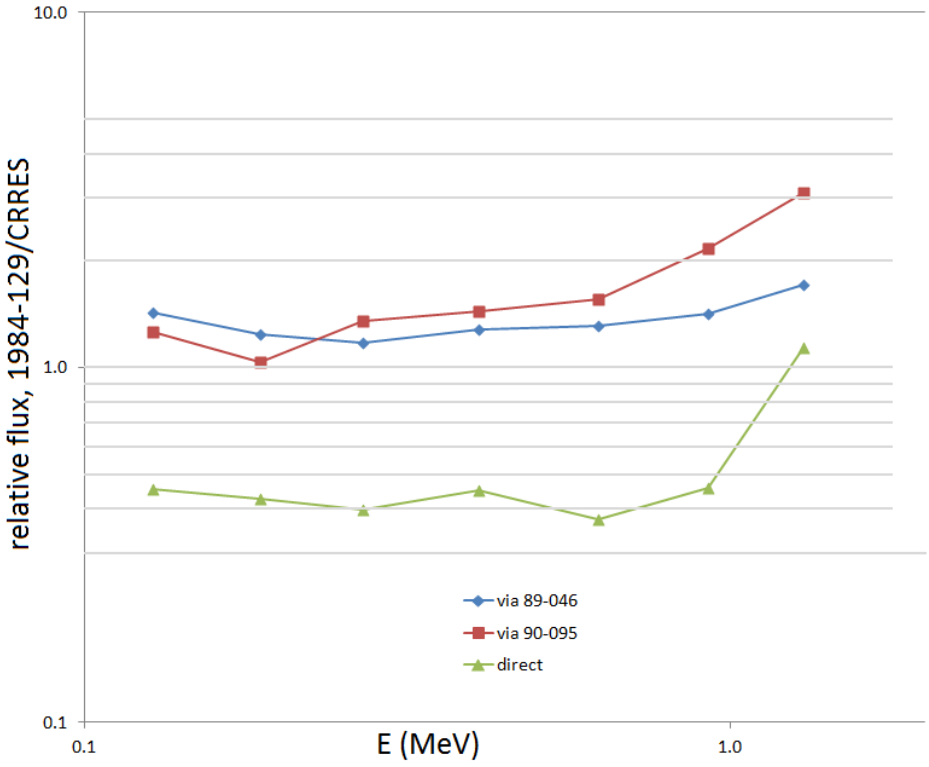

Figure 2: Omnidirectional flux ratios vs. channel energy, 1984-129 vs. CRRES

5. CONCLUSIONS

This report has presented results for cross calibration between sensors on nine LANL-GEO satellites. These results use all unidirectional data for LANL-97A and LANL-02A. For LANL-01A, 1991-080, and 1994-084, results are for Kp-restricted omnidirectional data since we have little or no unidirectional data in hand. Regarding the two satellites that were directly cross-calibrated with CRRES [6], GEO-GEO comparisons for 1989-046 are slightly less variable than comparisons for 1990-095.

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[6] Johnston, W. R. (2013), GEO-CRRES cross-calibration results for AE9 development, AFRL Technical Report, in preparation.

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APPENDIX A: SOPA COMPARISONS, ADDITIONAL FIGURES

The following figures show cross calibration results for the SOPA detectors:

- Figures A1-A11: Scatter plots of GEO2 flux vs. GEO1 flux by energy channel (blue points). Red lines show best linear fit to log fluxes, black line shows y=x (nominal agreement).
- Figures A12-A27: Ratio of GEO2 to GEO1 fluxes vs. channel energy. Each blue line is the ratio of fluxes vs. energy for one day, the thick black line is the median, and the two thin black lines give 2.5^{th} and 97.5^{th} percentiles (thus encompassing 95% of the range).
- Figures A28-A38: Histograms of flux ratios, with median offset (blue line) and notional agreement (black line).

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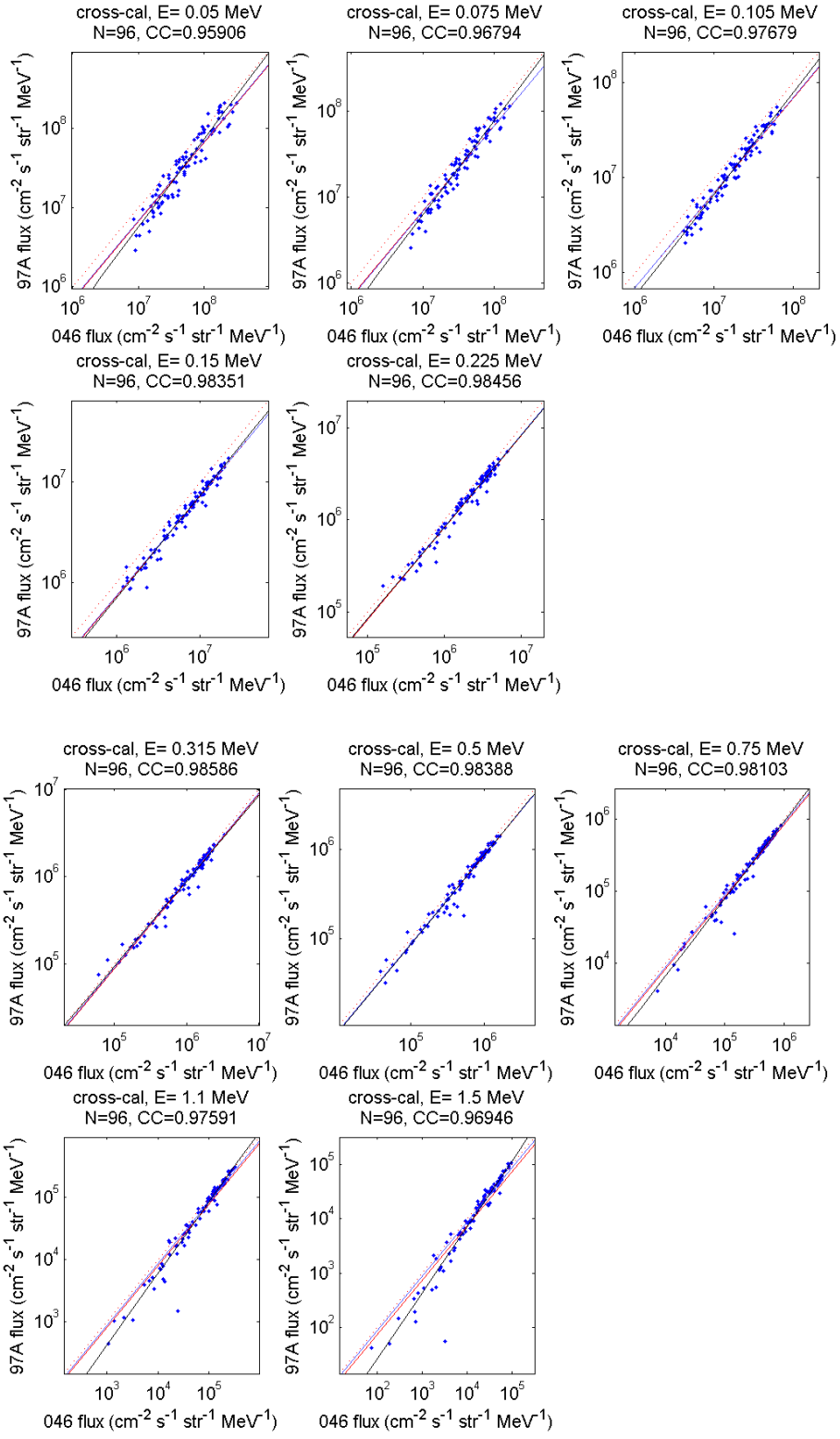

Figure A1: Scatter plots for the 10 energy channels, 1989-046 and LANL-97A

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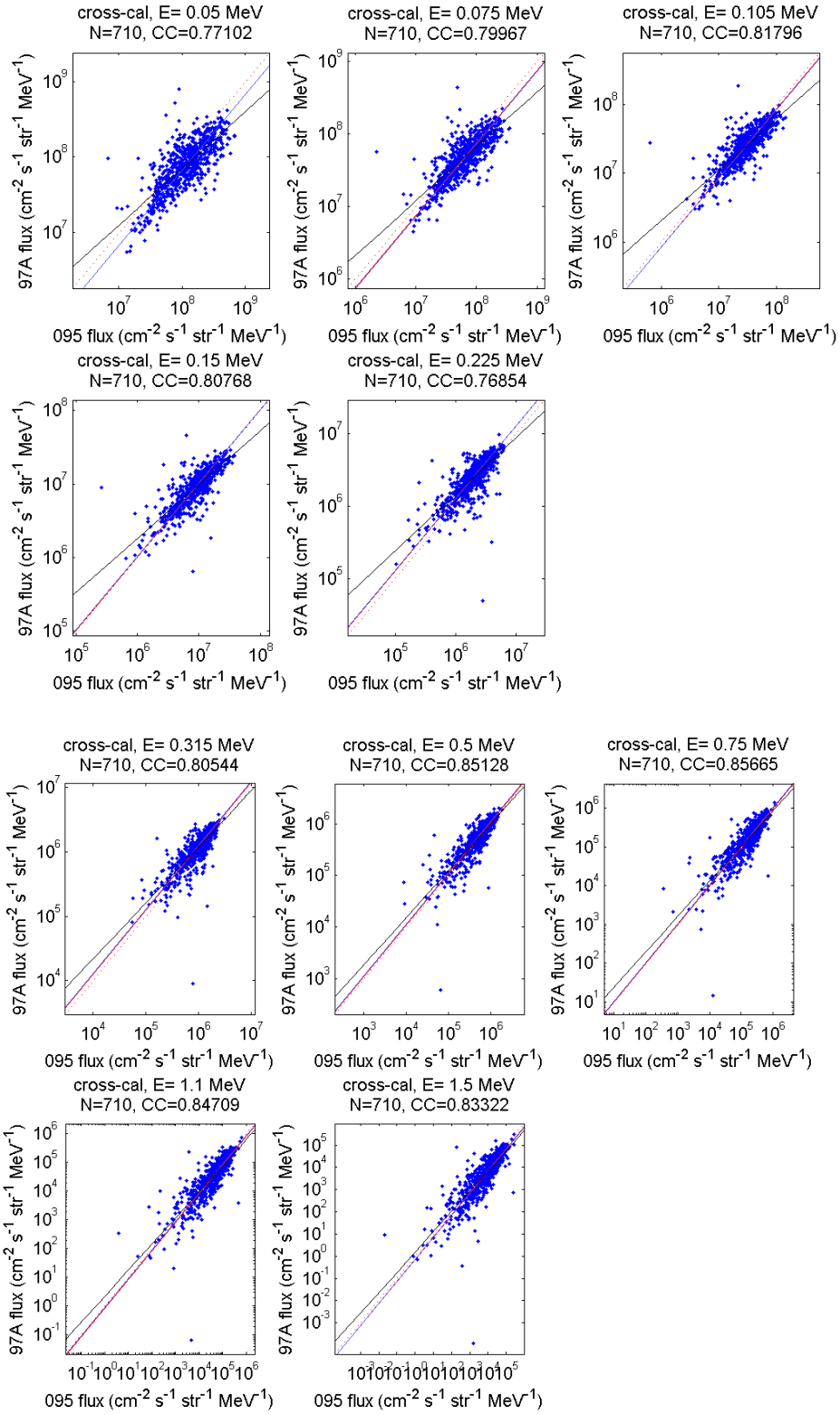

Figure A2: Scatter plots for the 10 energy channels, 1990-095 and LANL-97A

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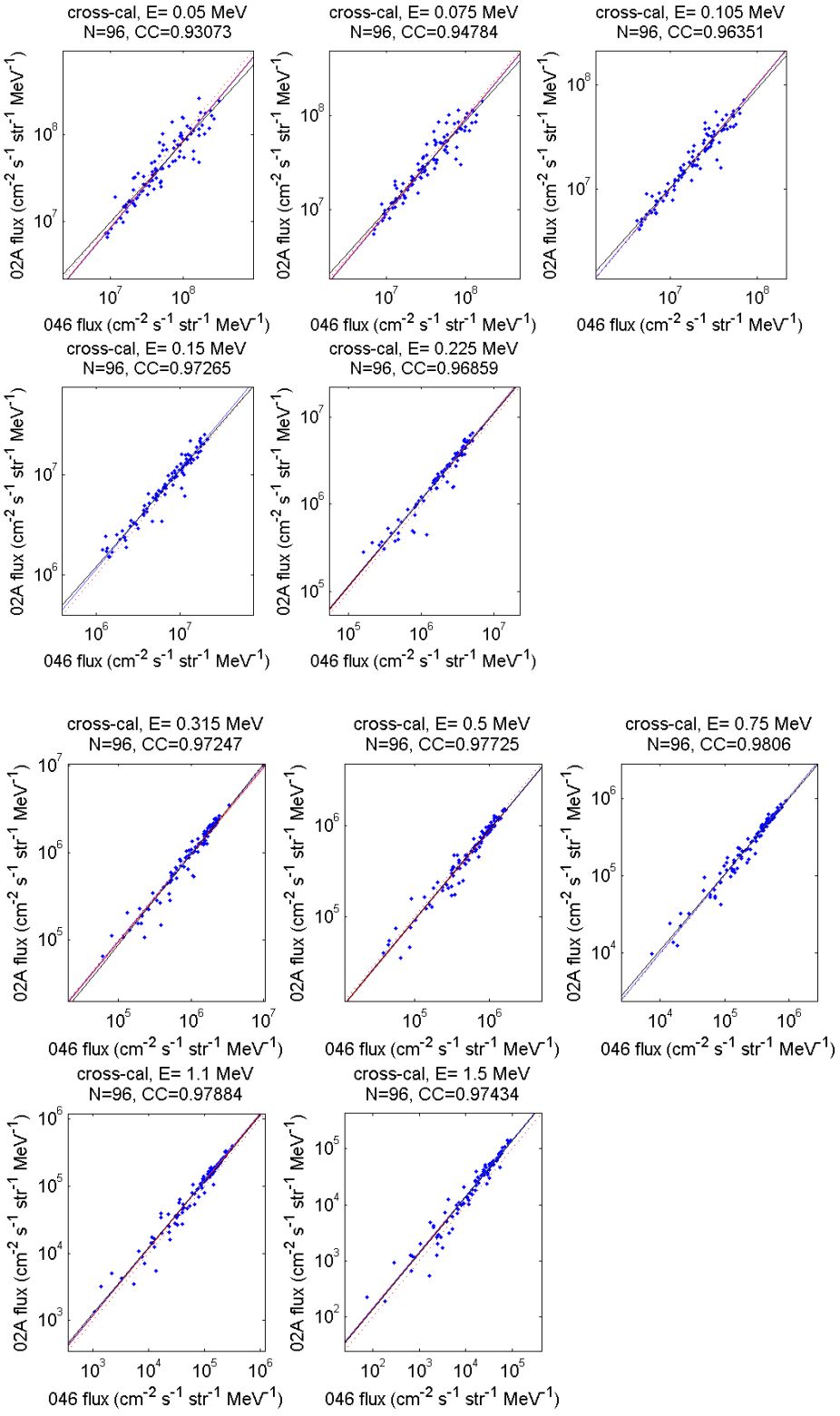

Figure A3: Scatter plots for the 10 energy channels, 1989-046 and LANL-02A

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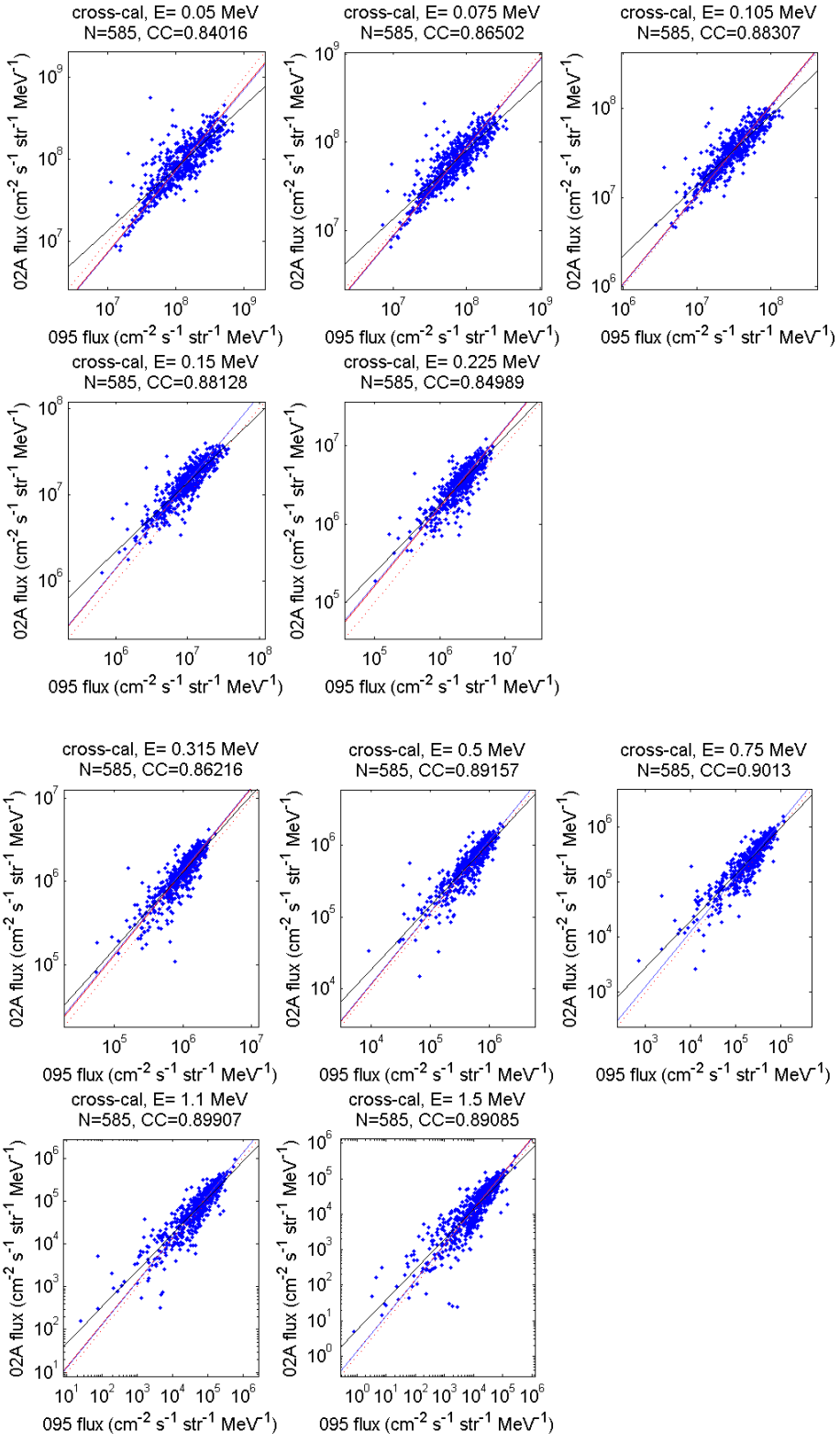

Figure A4: Scatter plots for the 10 energy channels, 1990-095 and LANL-02A

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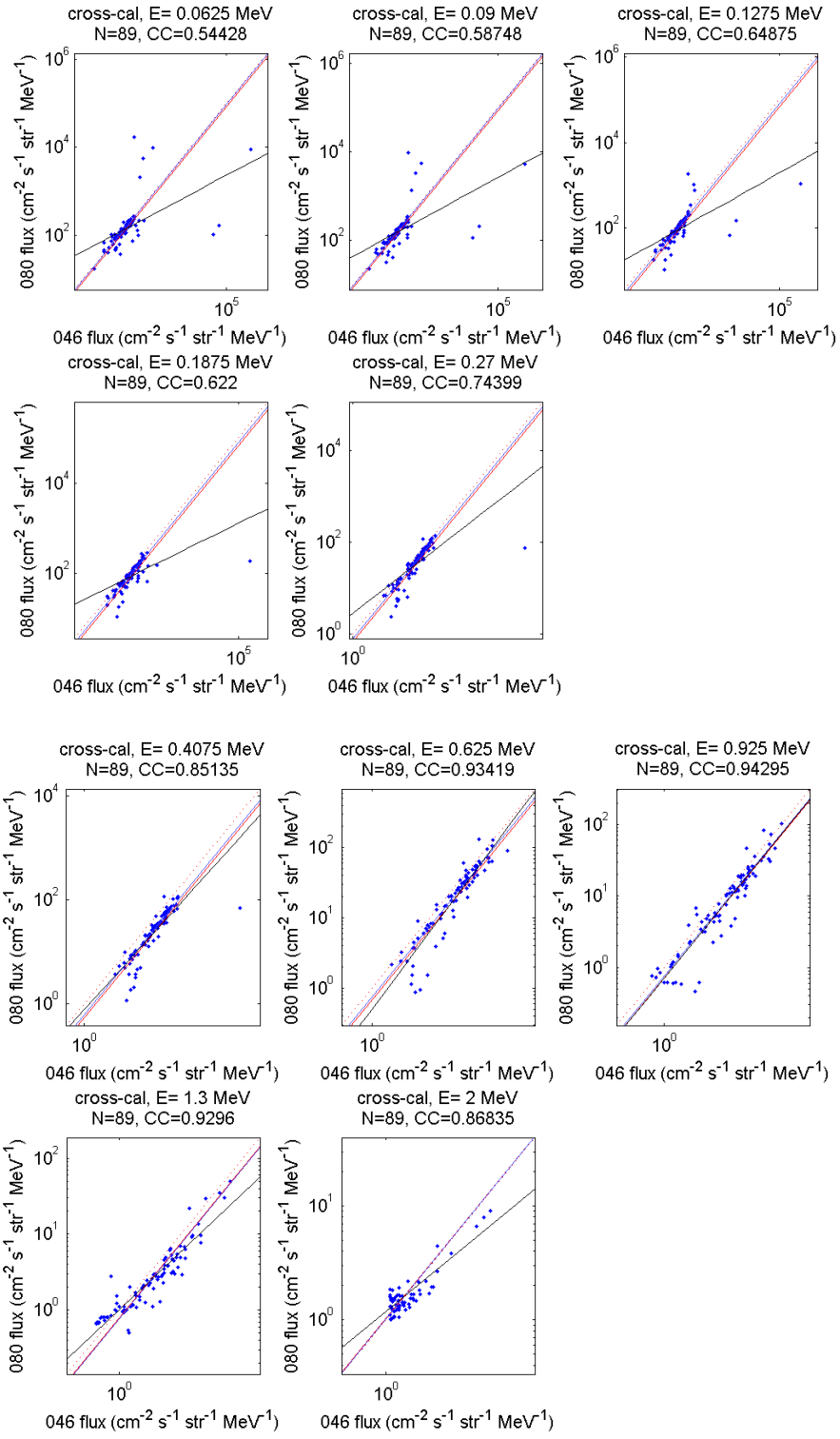

Figure A5: Scatter plots for the 10 energy channels, 1989-046 and 1991-080

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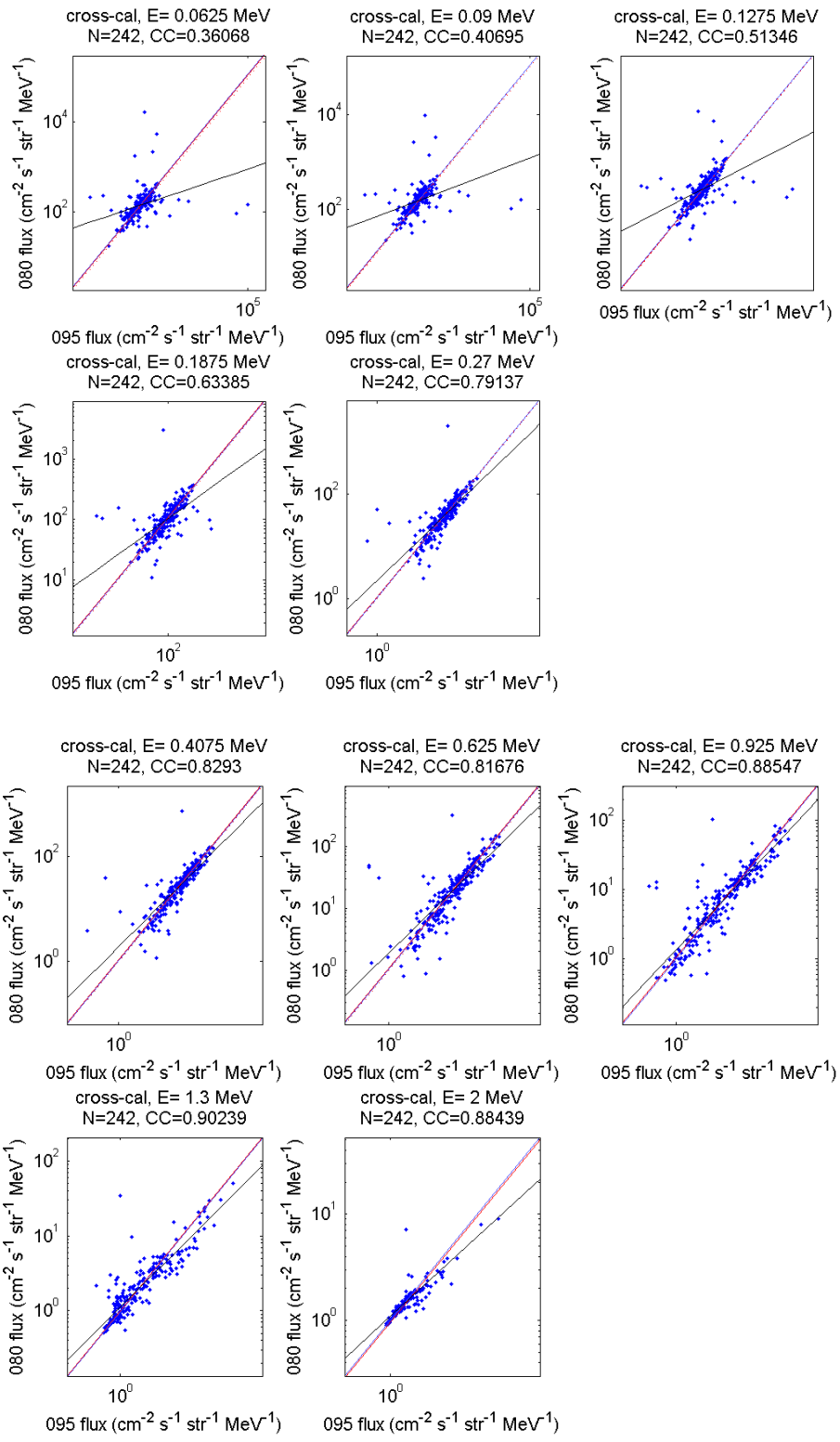

Figure A6: Scatter plots for the 10 energy channels, 1990-095 and 1991-080

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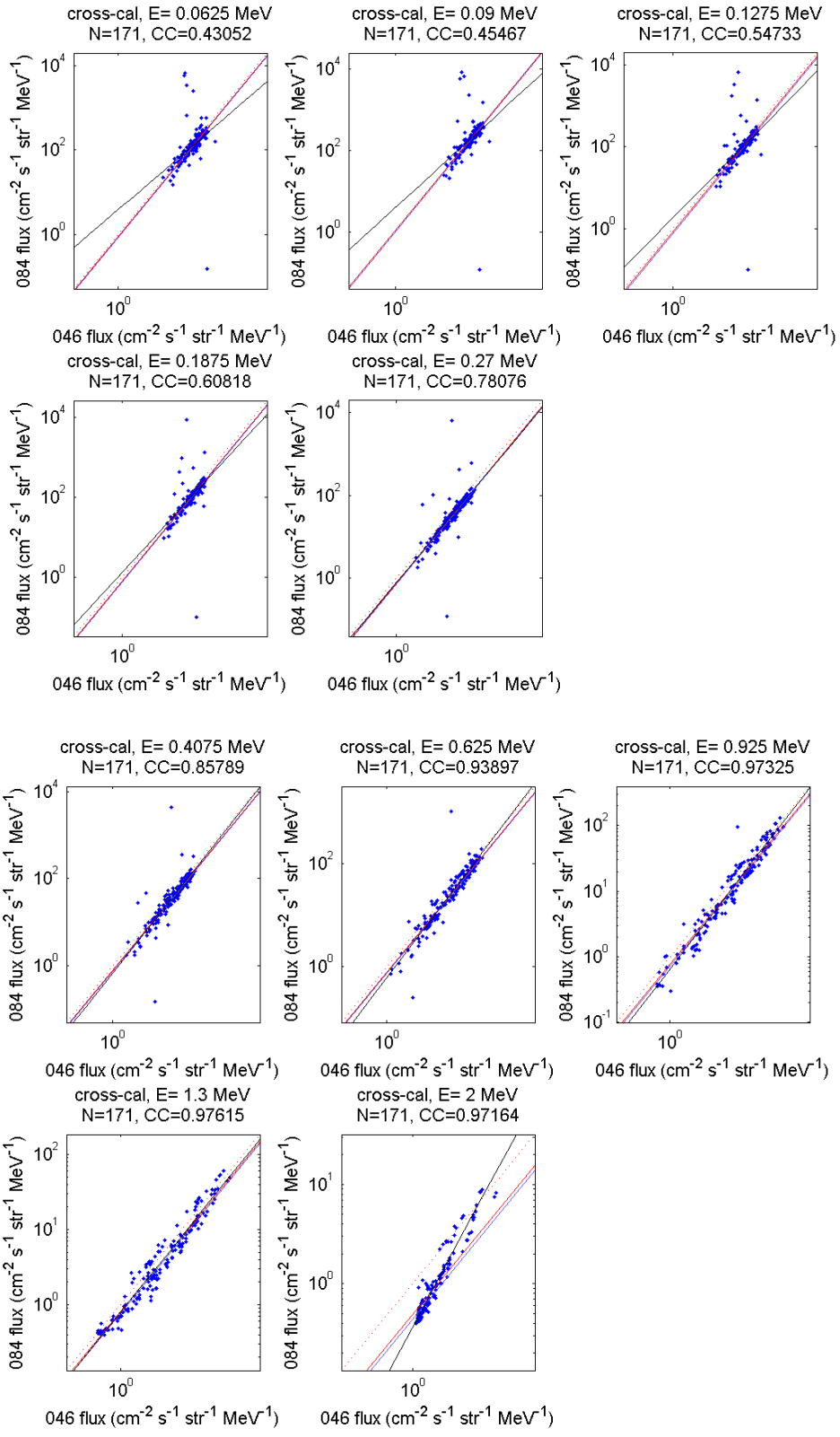

Figure A7: Scatter plots for the 10 energy channels, 1989-046 and 1994-084

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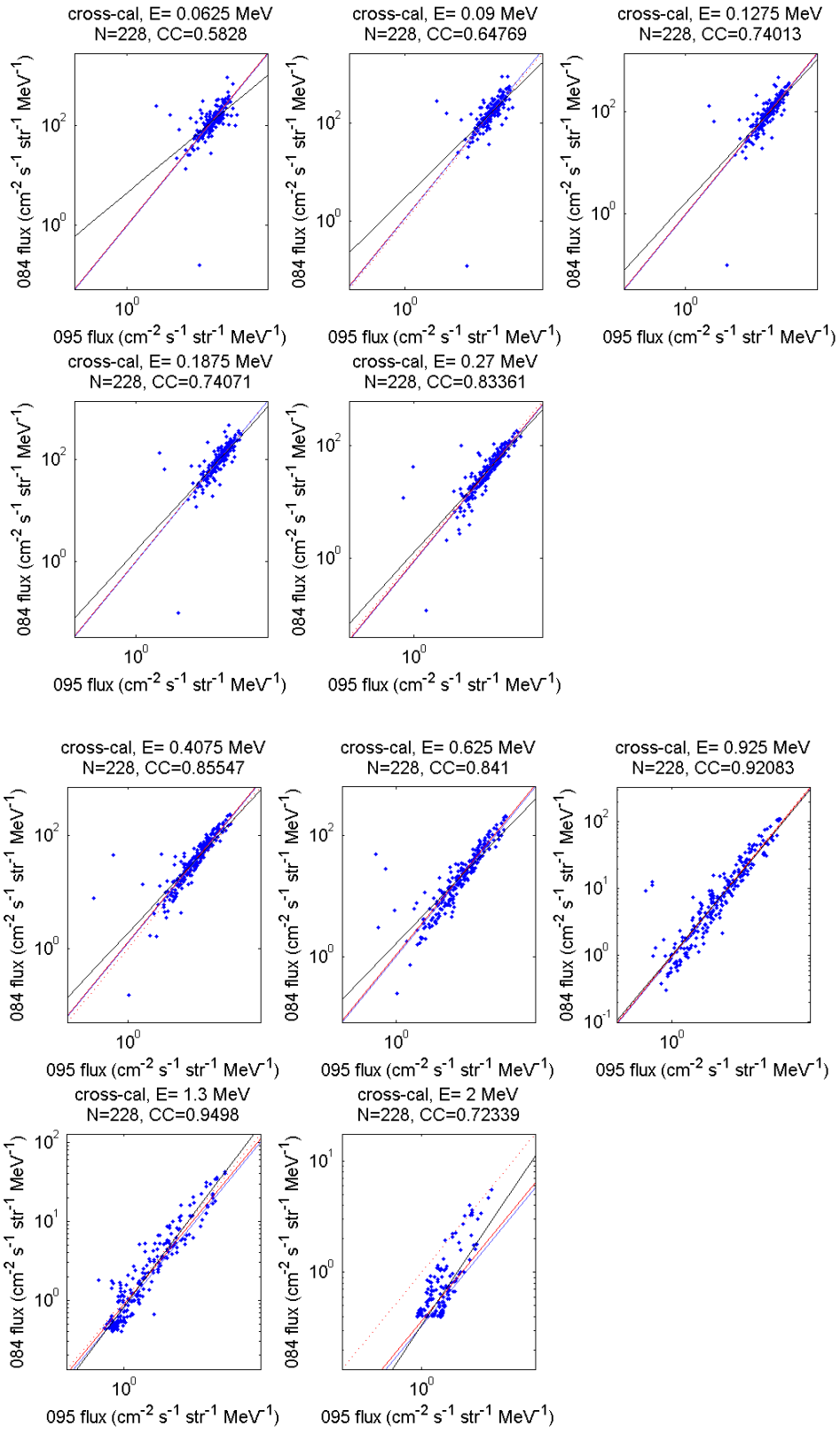

Figure A8: Scatter plots for the 10 energy channels, 1990-095 and 1994-084

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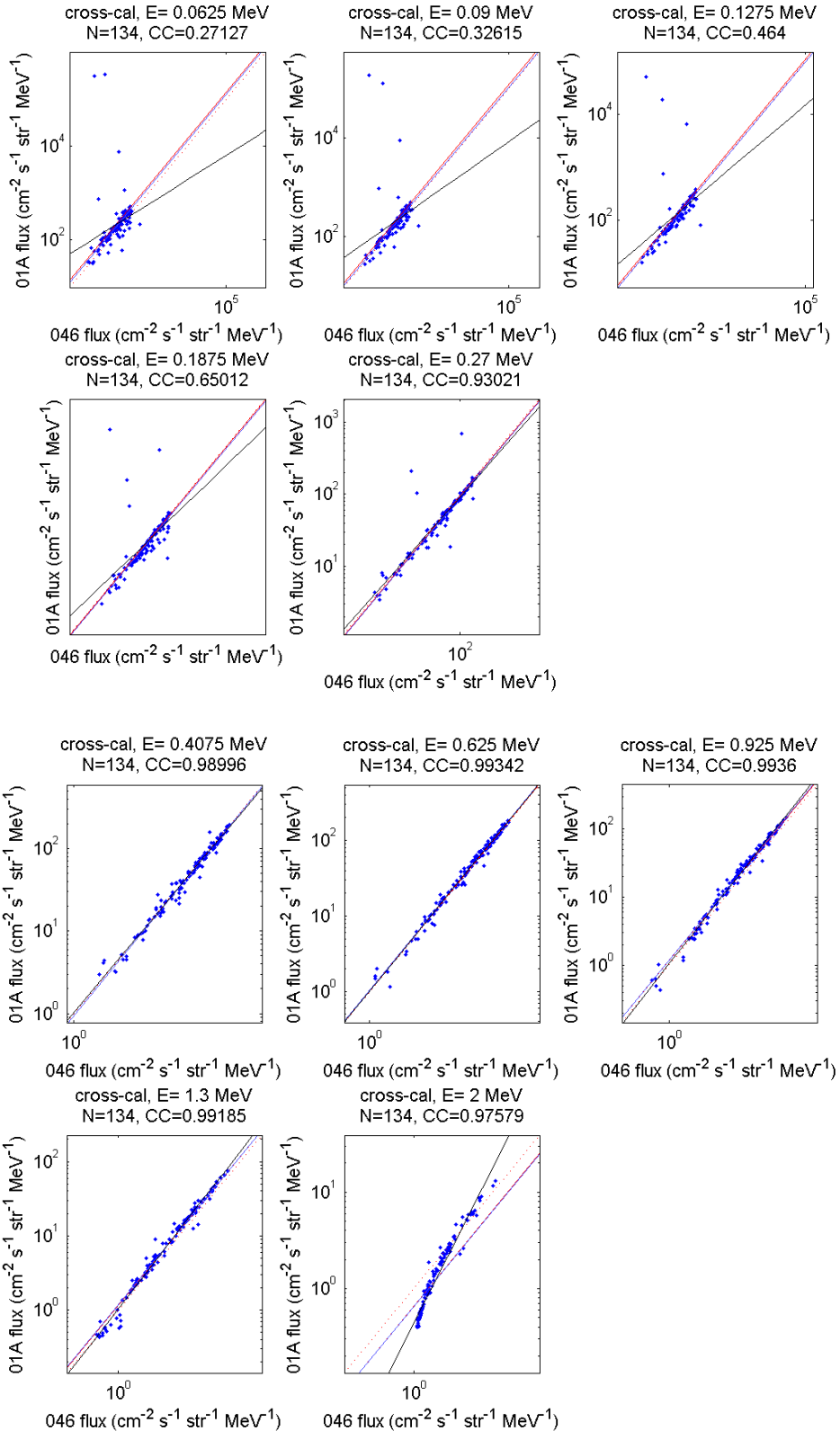

Figure A9: Scatter plots for the 10 energy channels, 1989-046 and LANL-01A

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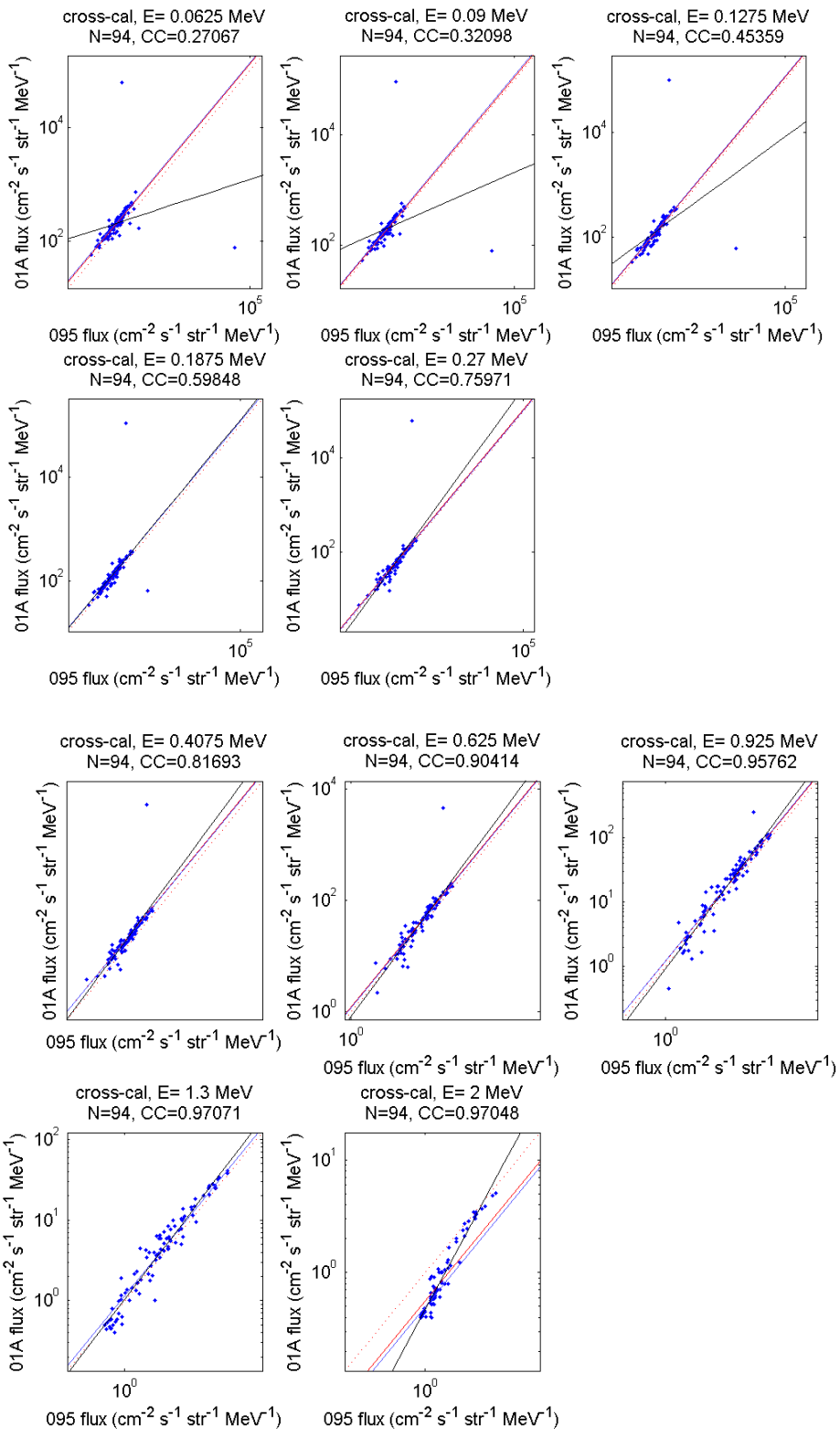

Figure A10: Scatter plots for the 10 energy channels, 1990-095 and LANL-01A

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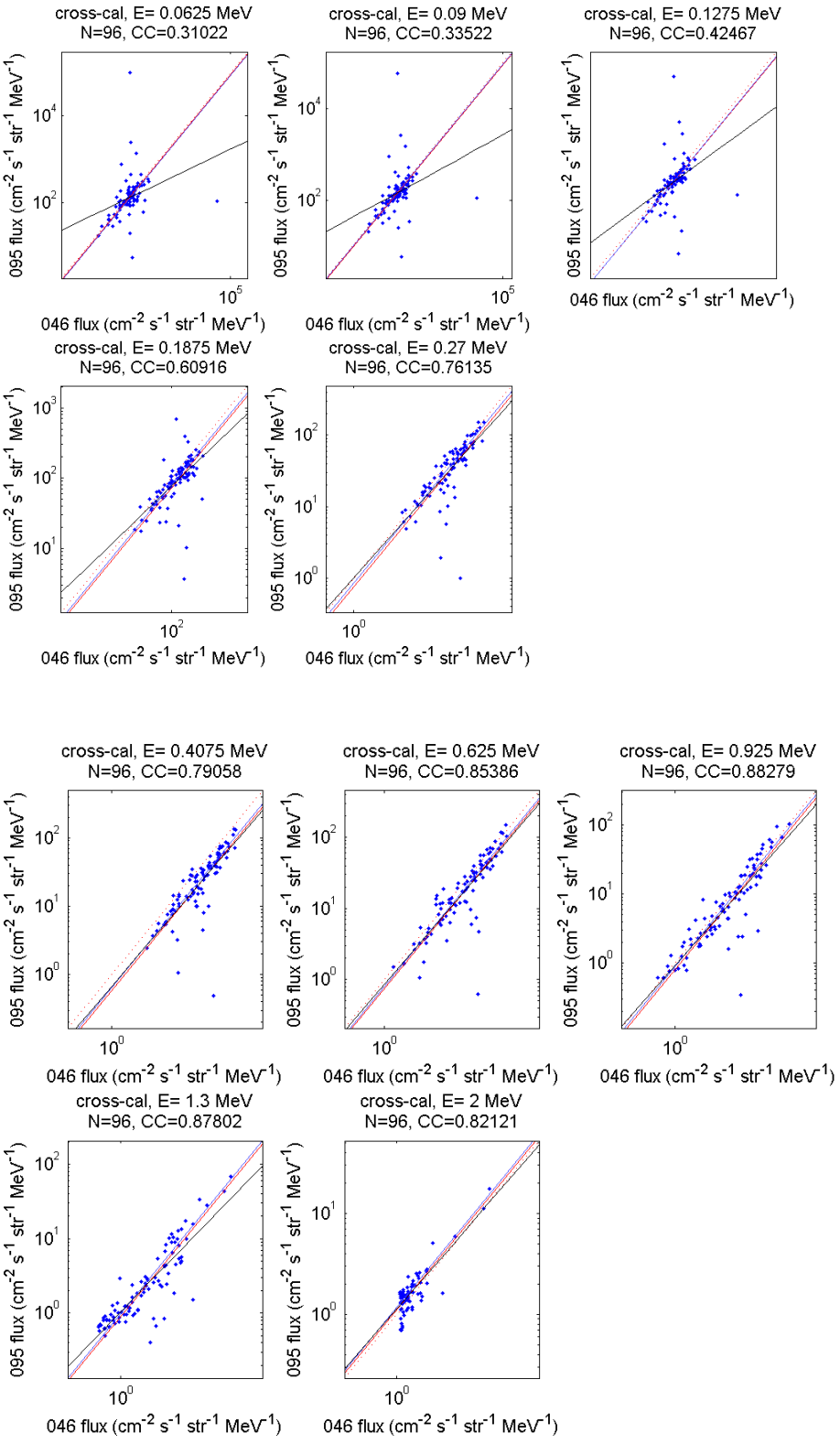

Figure A11: Scatter plots for the 10 energy channels, 1989-046 and 1990-095 (daily averages, Kp<2, last 48 hr)

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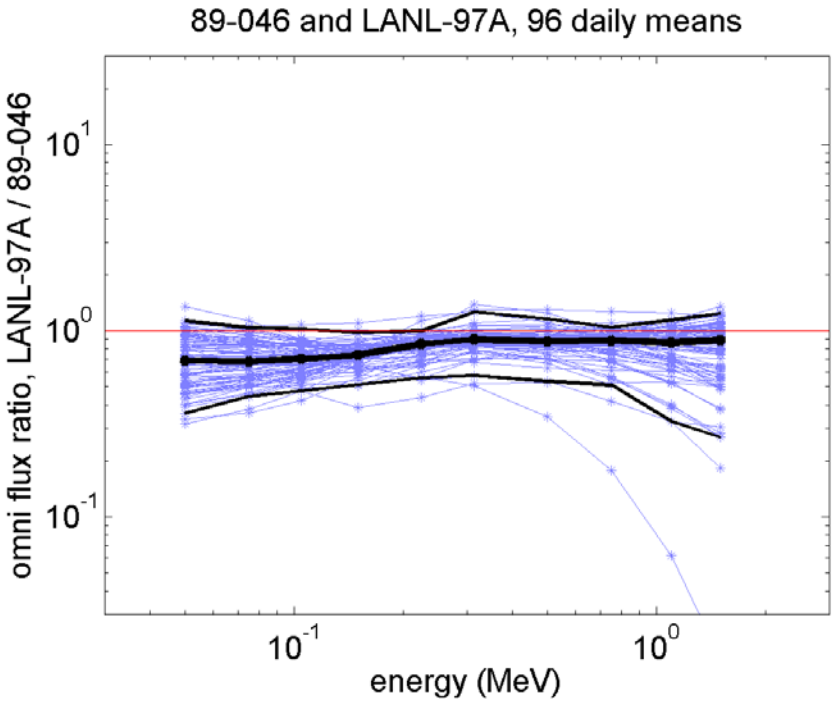

Figure A12: Flux ratios vs. channel energy, LANL-97A/1989-046, type C data, all Kp

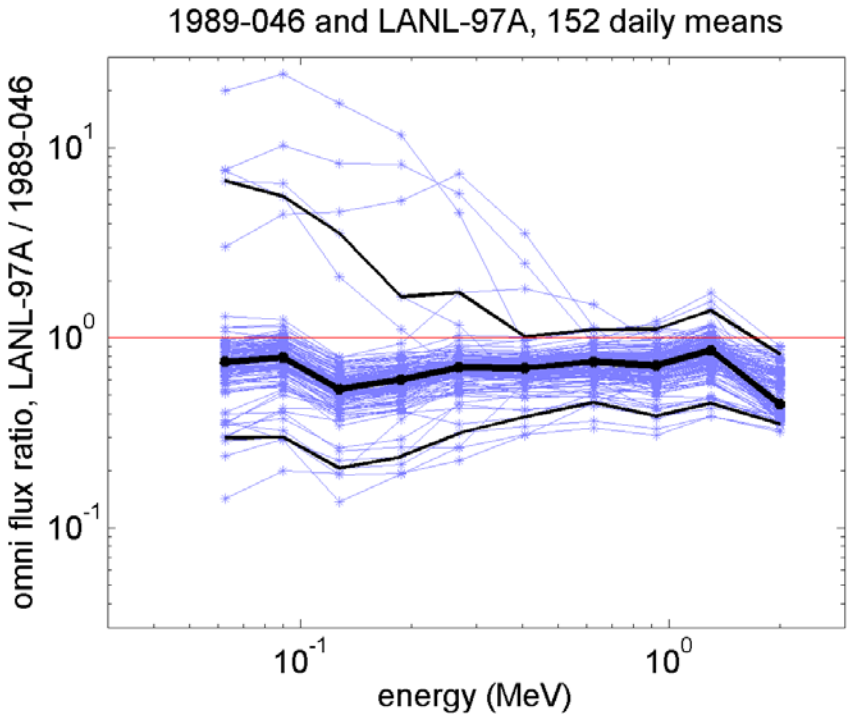

Figure A13: Flux ratios vs. channel energy, LANL-97A/1989-046, type B data, Kp<2

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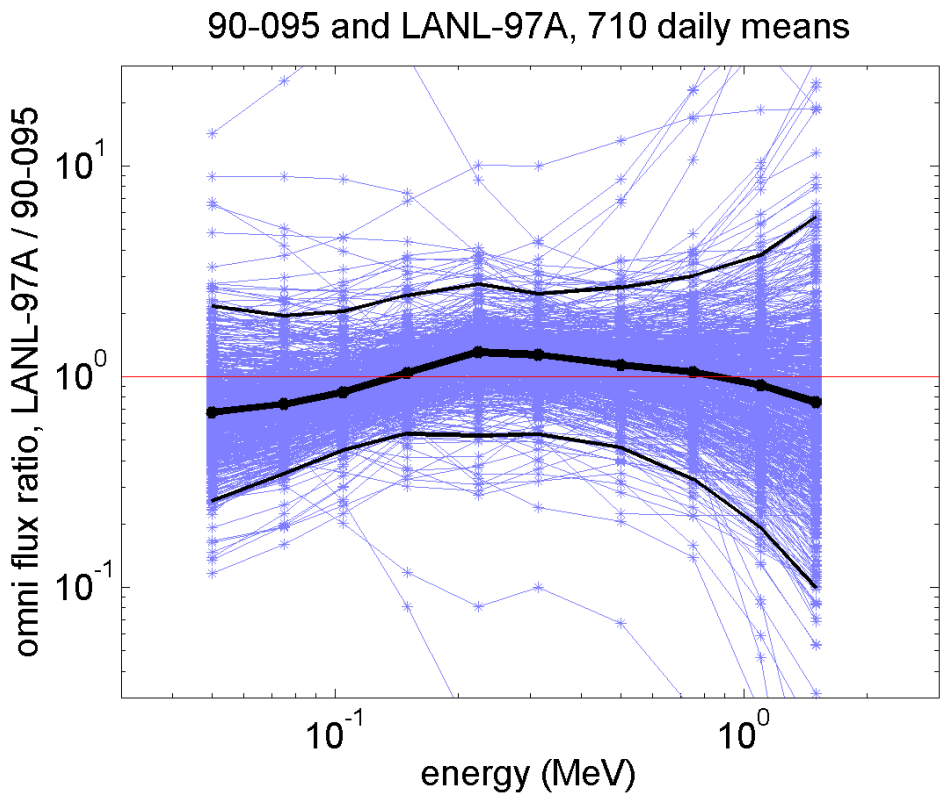

Figure A14: Flux ratios vs. channel energy, LANL-97A/1990-095, type C data, all Kp

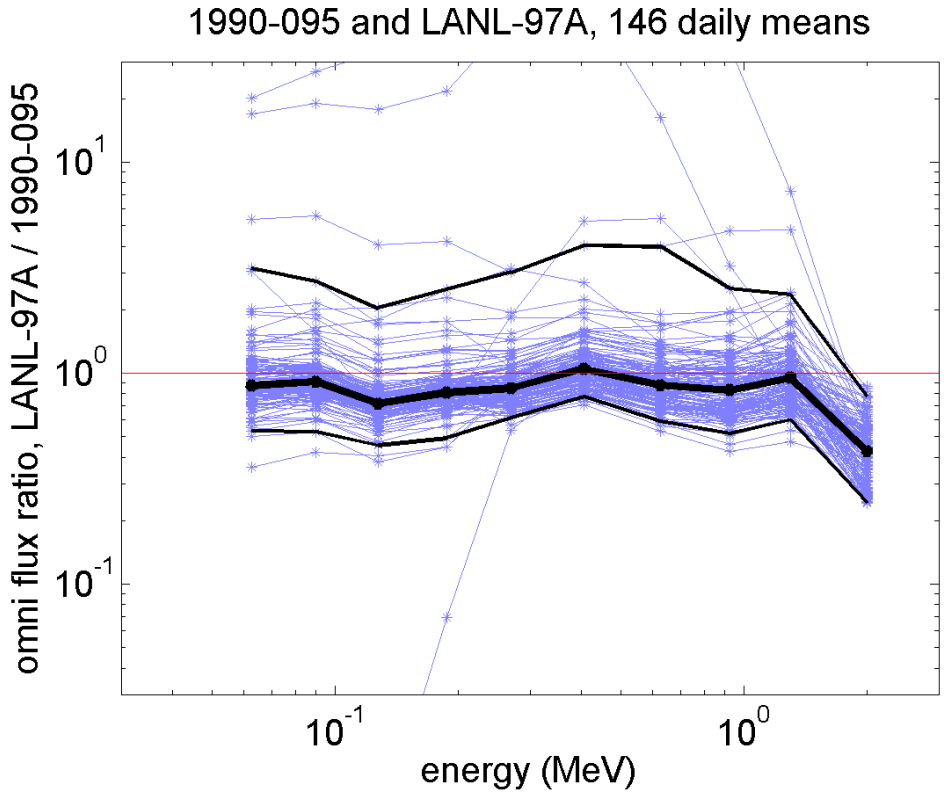

Figure A15: Flux ratios vs. channel energy, LANL-97A/1990-095, type B data, Kp<2

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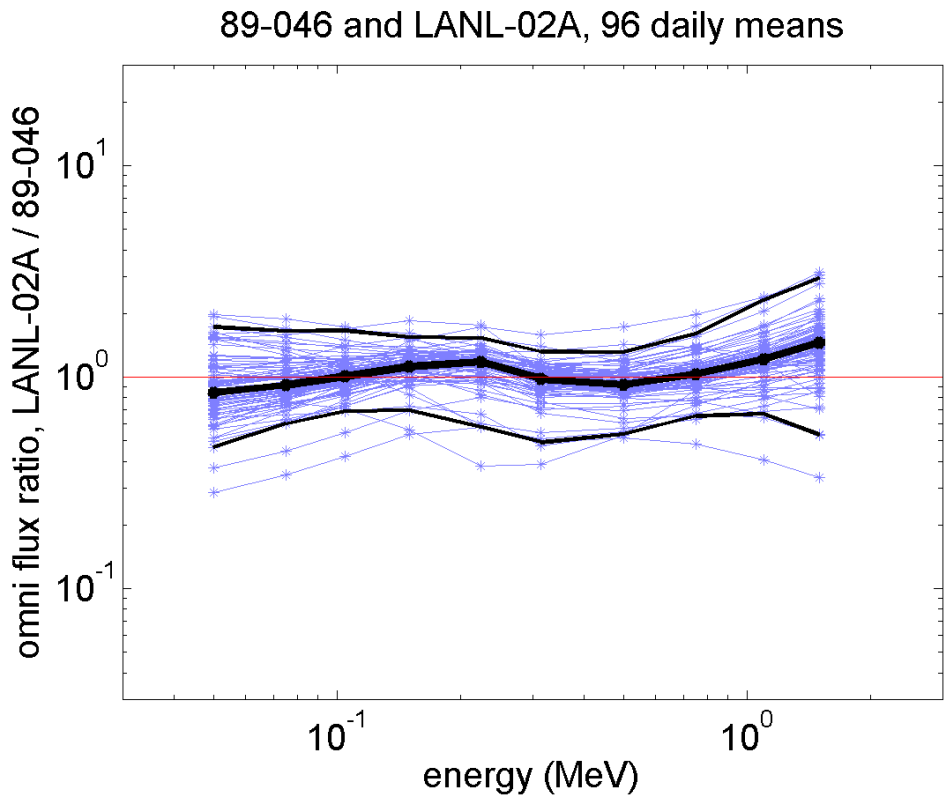

Figure A16: Flux ratios vs. channel energy, LANL-02A/1989-046, type C data, all Kp

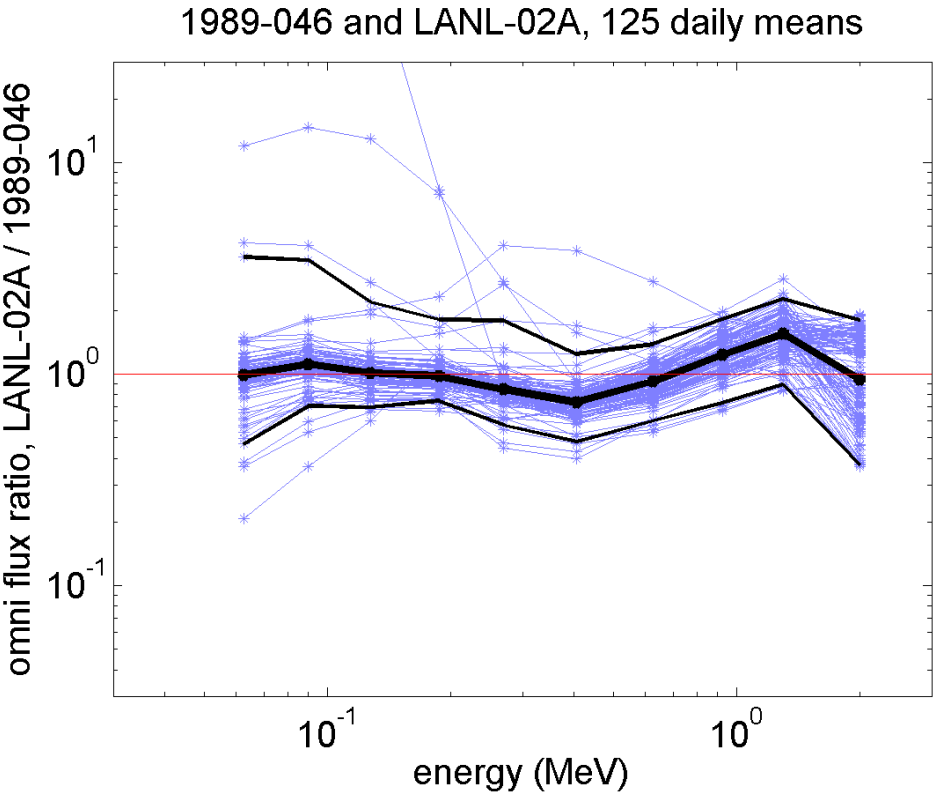

Figure A17: Flux ratios vs. channel energy, LANL-02A/1989-046, type B data, Kp<2

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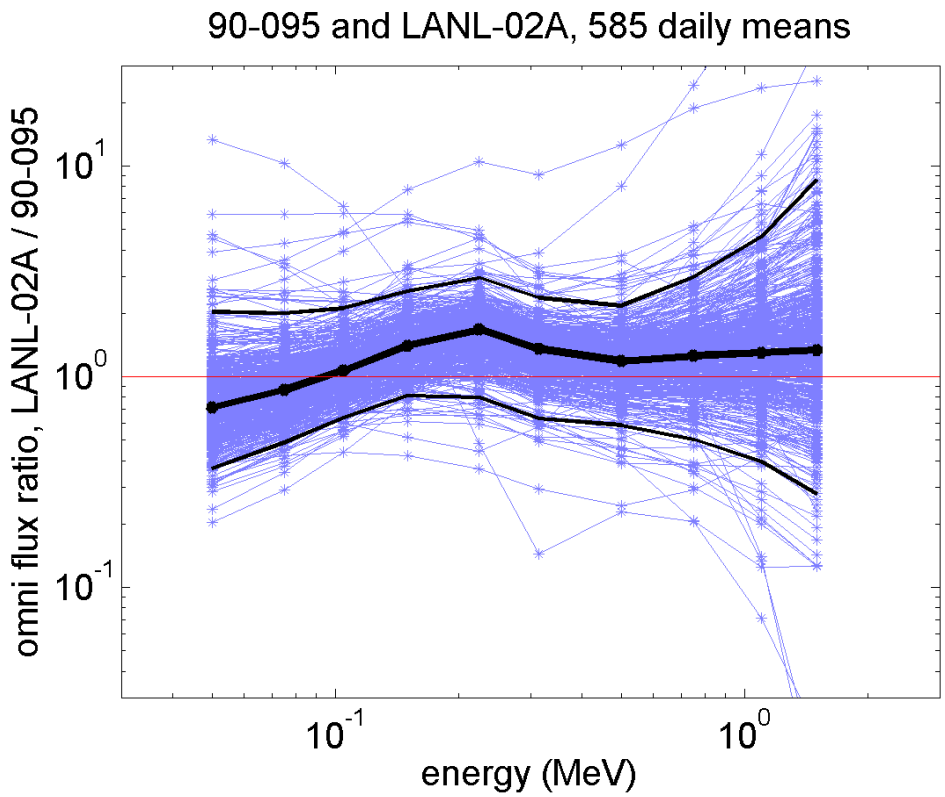

Figure A18: Flux ratios vs. channel energy, LANL-02A/1990-095, type C data, all Kp

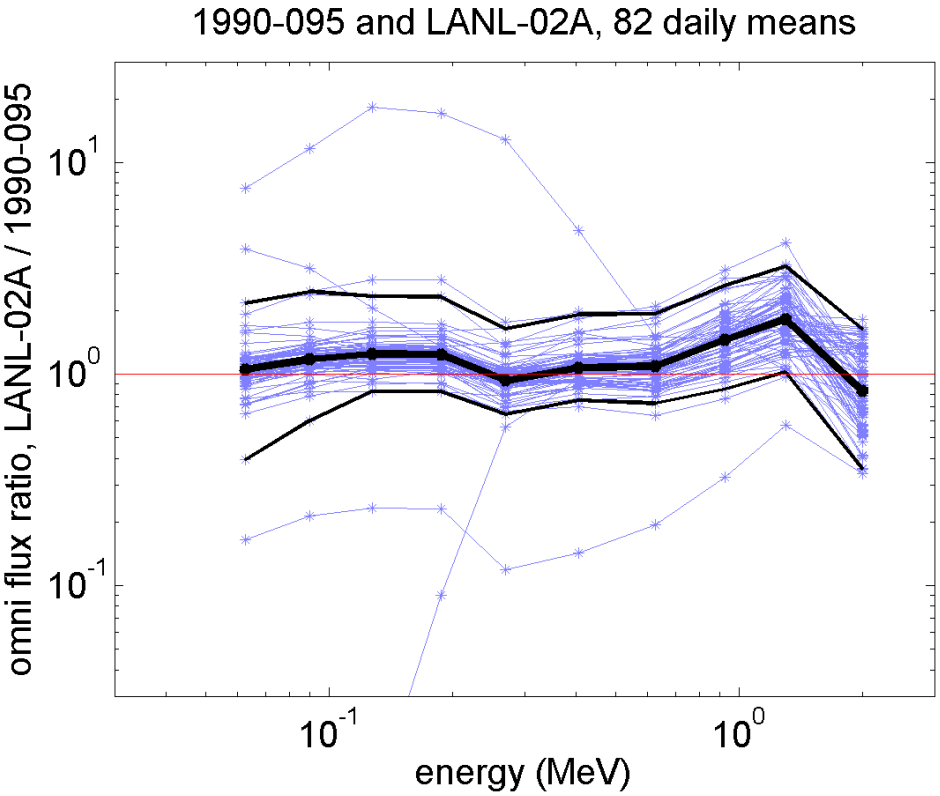

Figure A19: Flux ratios vs. channel energy, LANL-02A/1990-095, type B data, Kp<2

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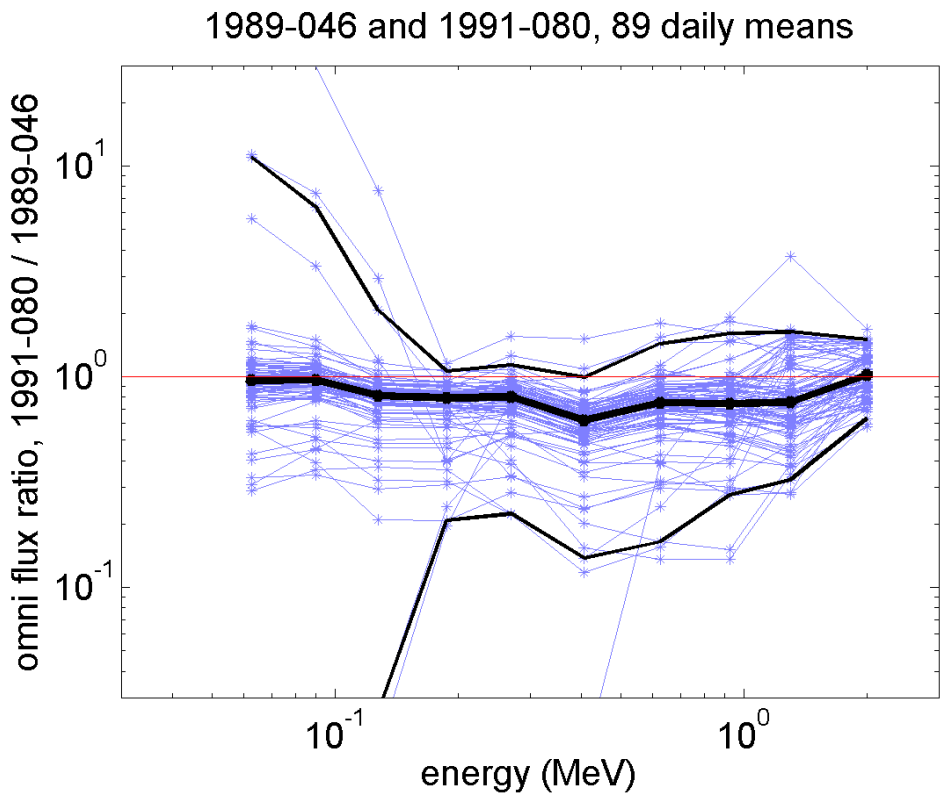

Figure A20: Flux ratios vs. channel energy, 1991-080/1989-046, type B data, Kp<2

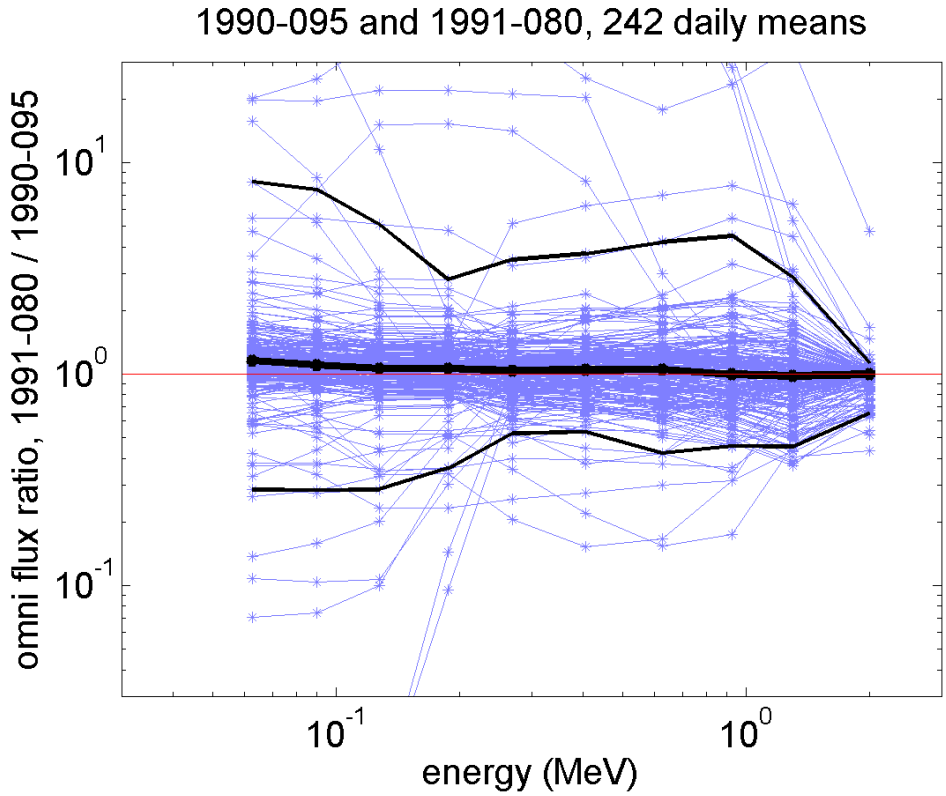

Figure A21: Flux ratios vs. channel energy, 1991-080/1990-095, type B data, Kp<2

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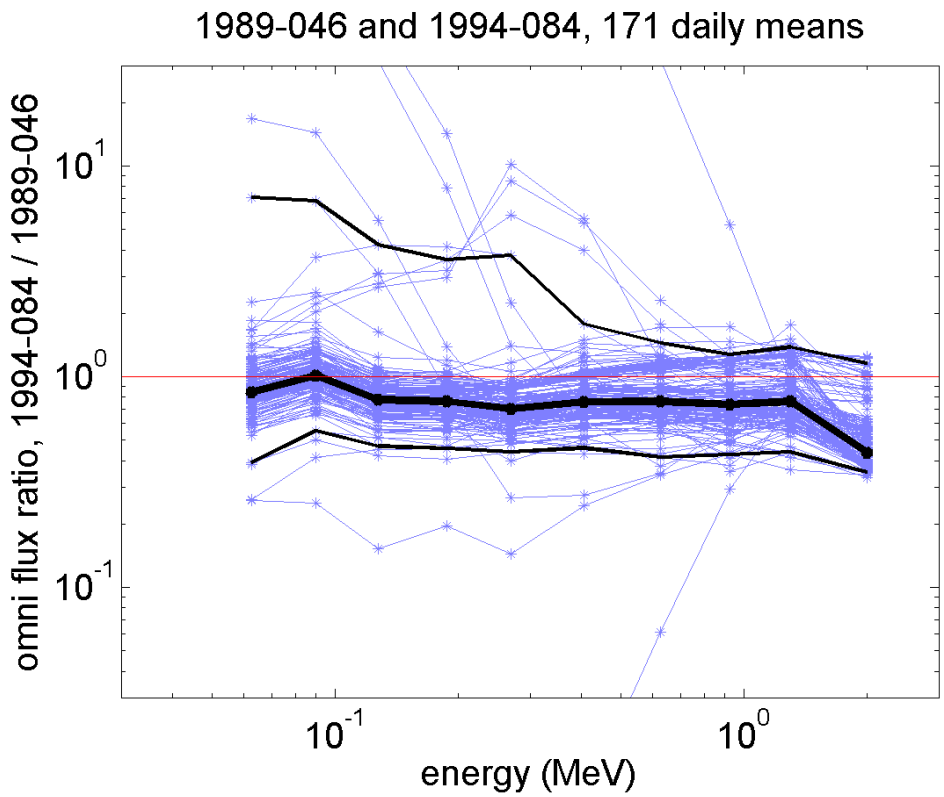

Figure A22: Flux ratios vs. channel energy, 1994-084/1989-046, type B data, Kp<2

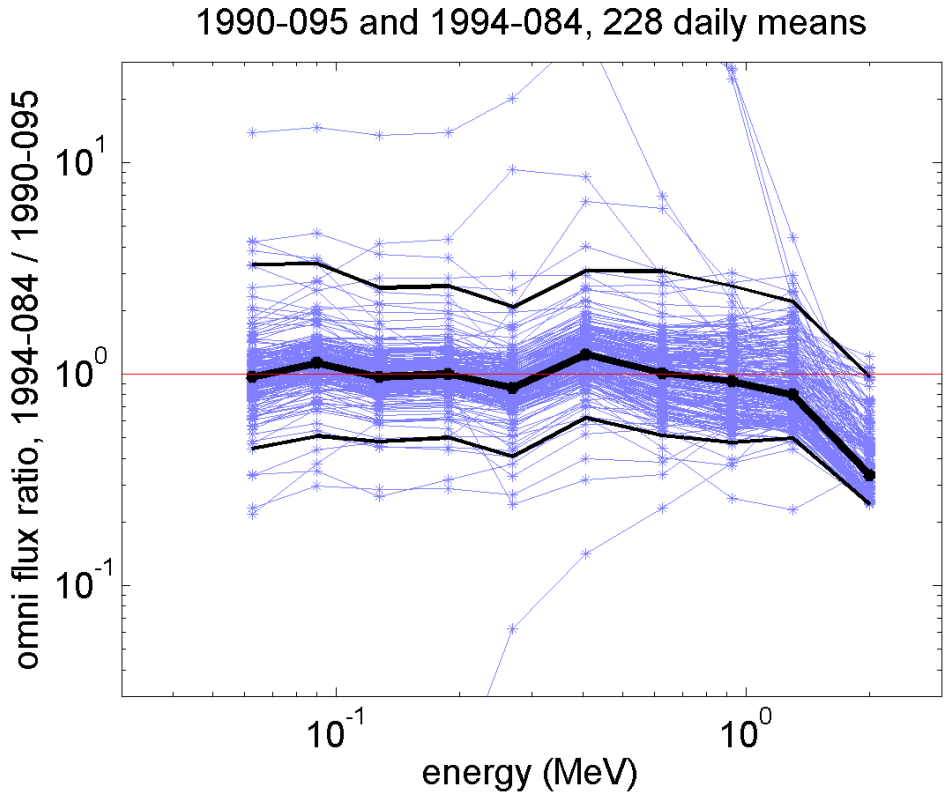

Figure A23: Flux ratios vs. channel energy, 1994-084/1990-095, type B data, Kp<2

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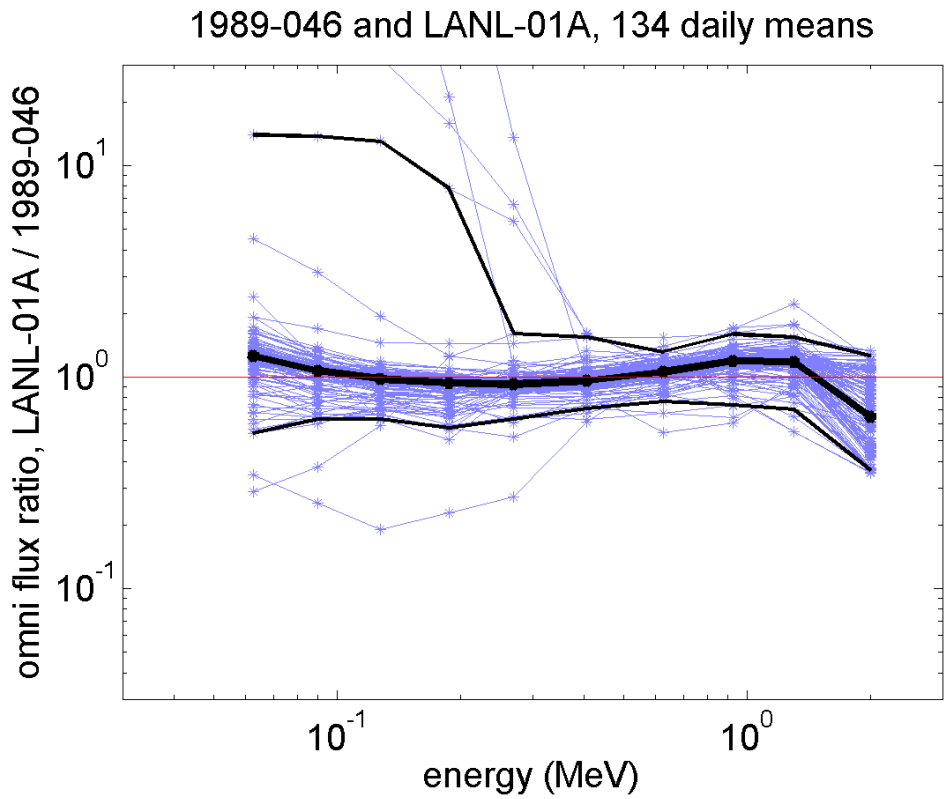

Figure A24: Flux ratios vs. channel energy, LANL-01A/1989-046, type B data, Kp<2

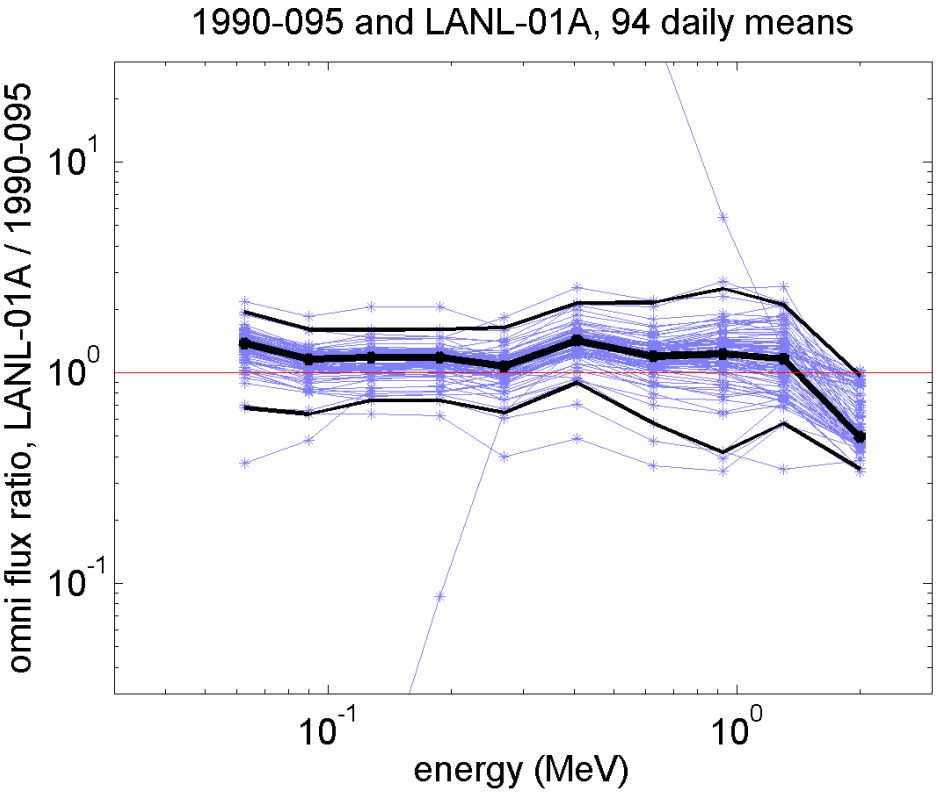

Figure A25: Flux ratios vs. channel energy, LANL-01A/1990-095, type B data, Kp<2

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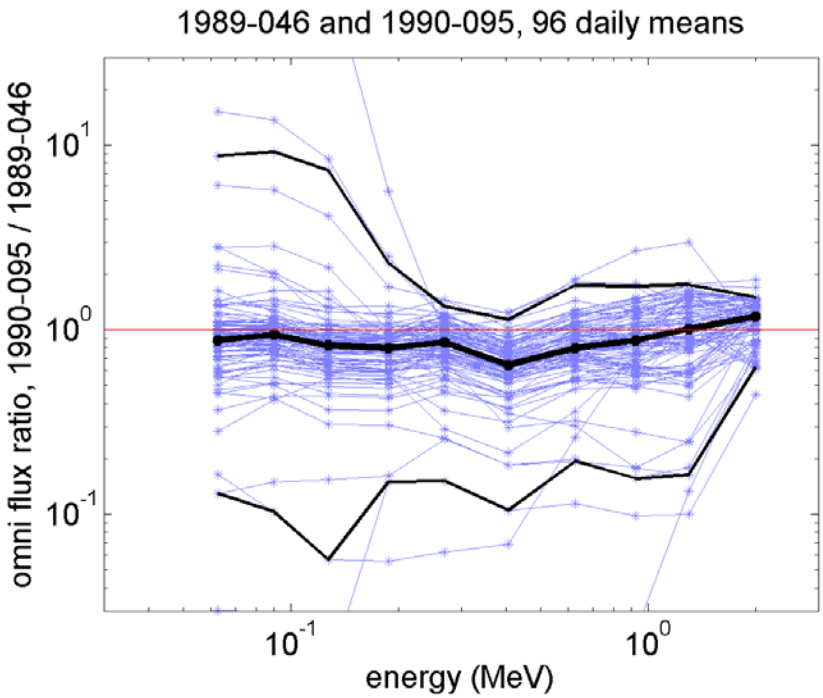

Figure A26: Flux ratios vs. channel energy, 1990-095/1989-046, type B data, Kp<2

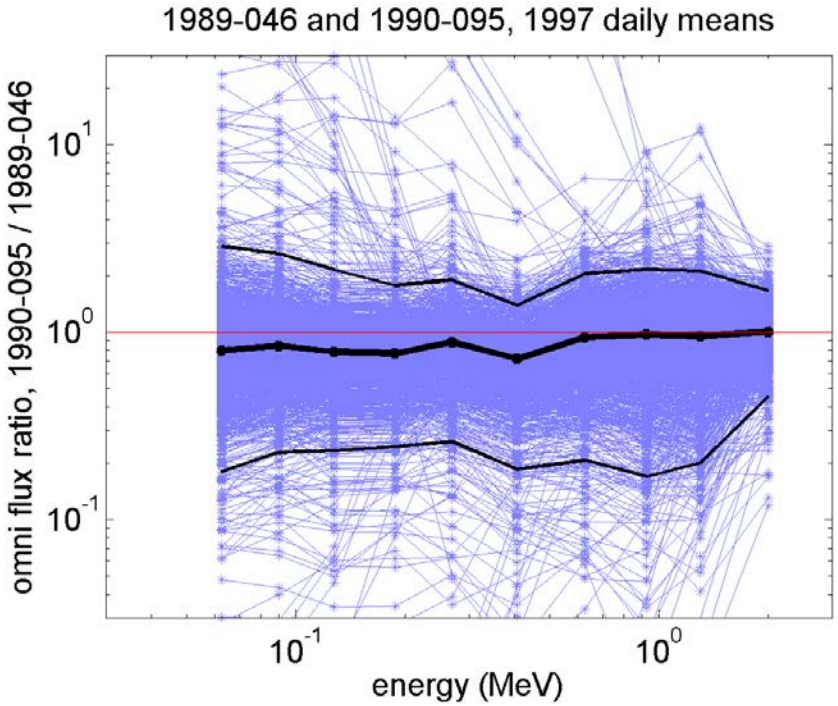

Figure A27: Flux ratios vs. channel energy, 1990-095/1989-046, type B data, all Kp

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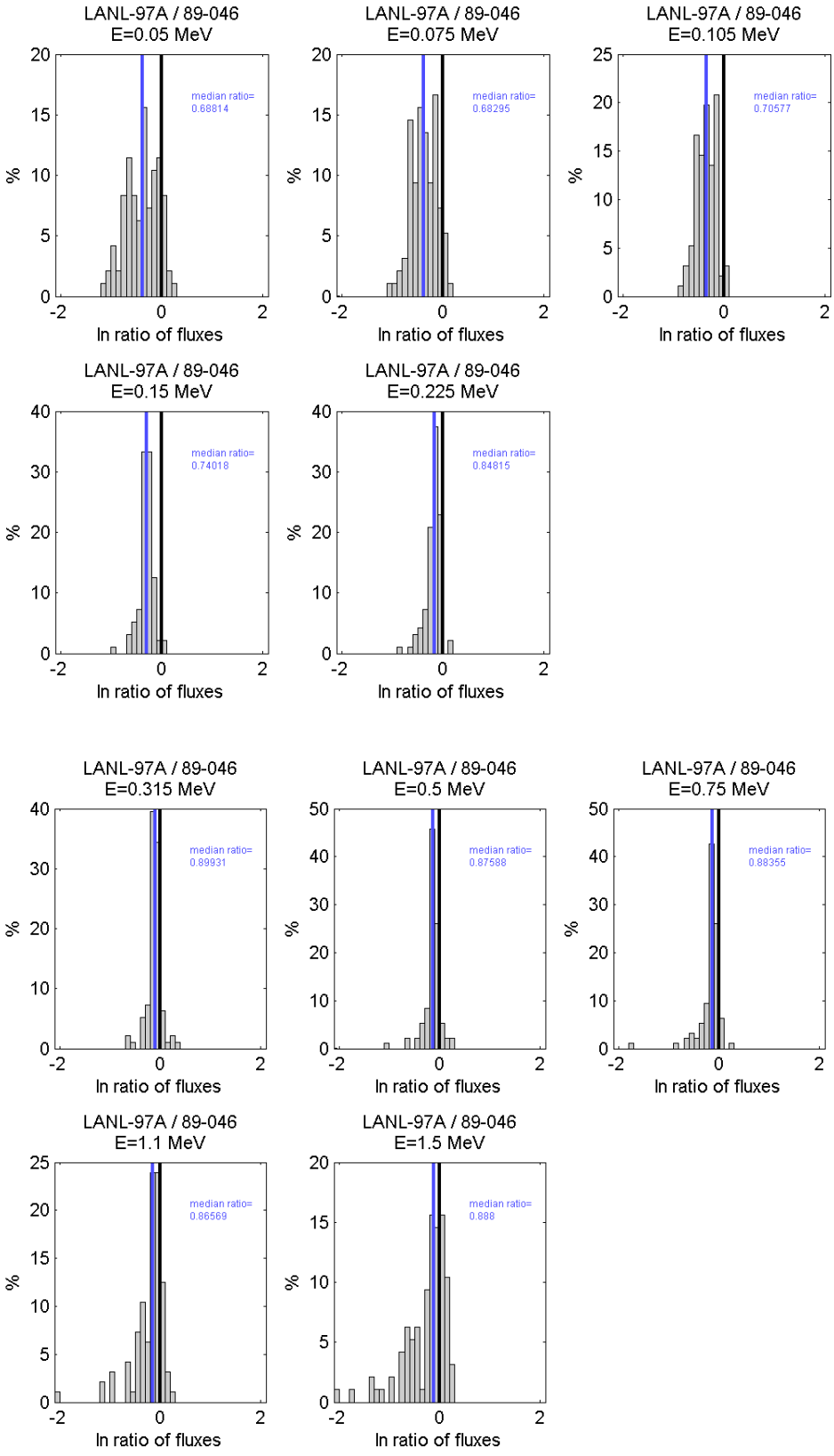

Figure A28: Histograms of flux ratios by energy channel, LANL-97A vs. 1989-046

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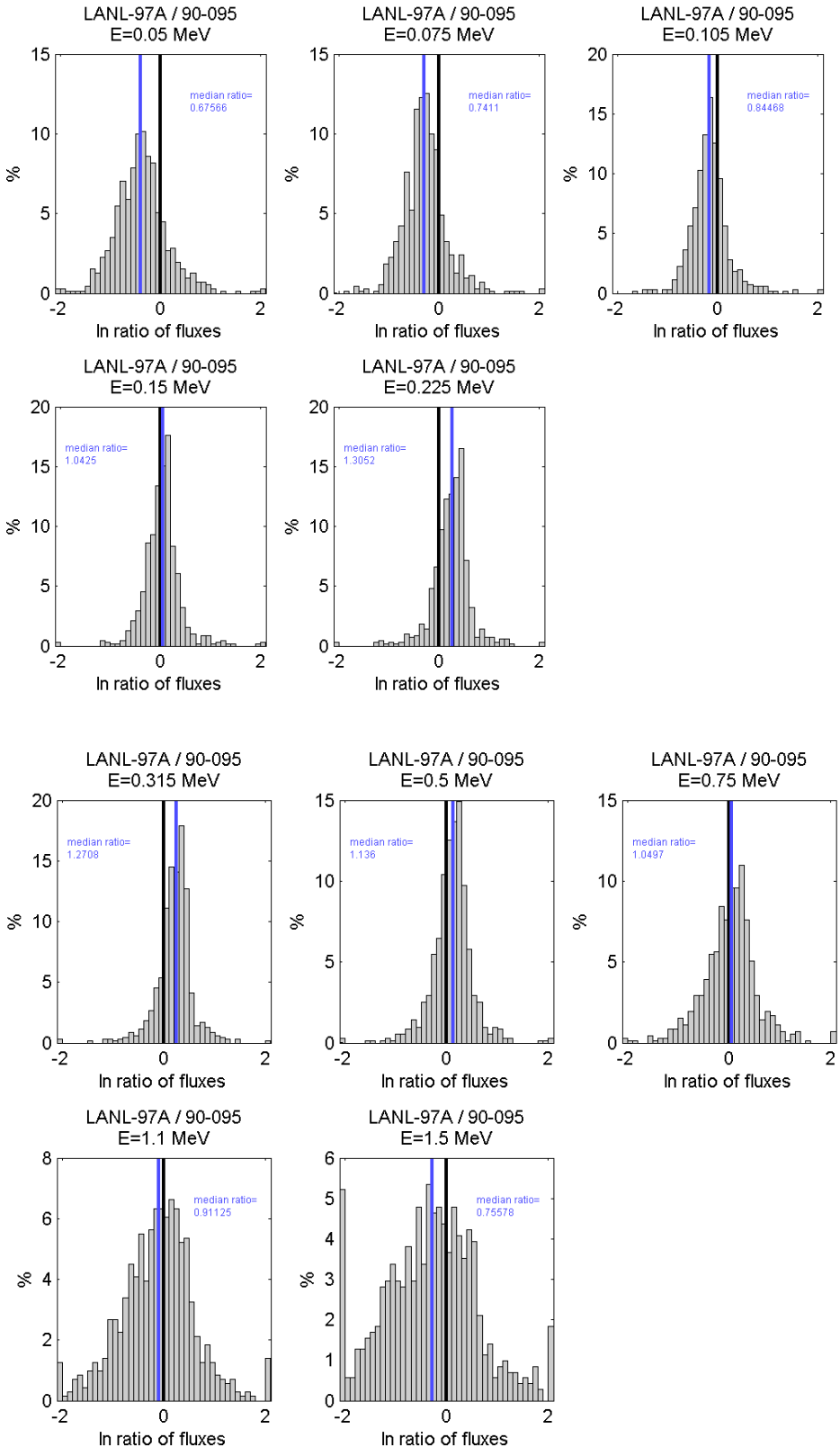

Figure A29: Histograms of flux ratios by energy channel, LANL-97A vs. 1990-095

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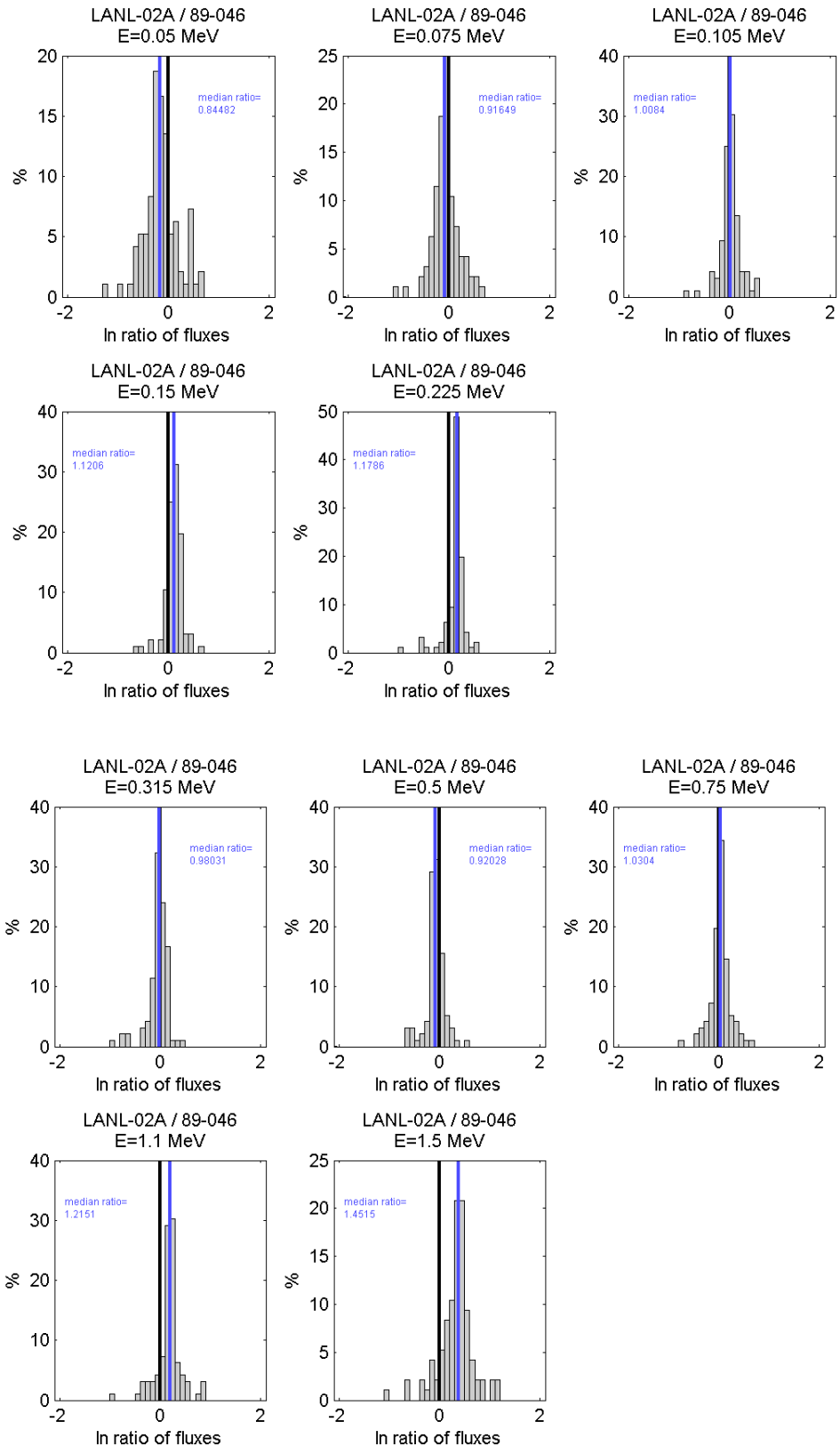

Figure A30: Histograms of flux ratios by energy channel, LANL-02A vs. 1989-046

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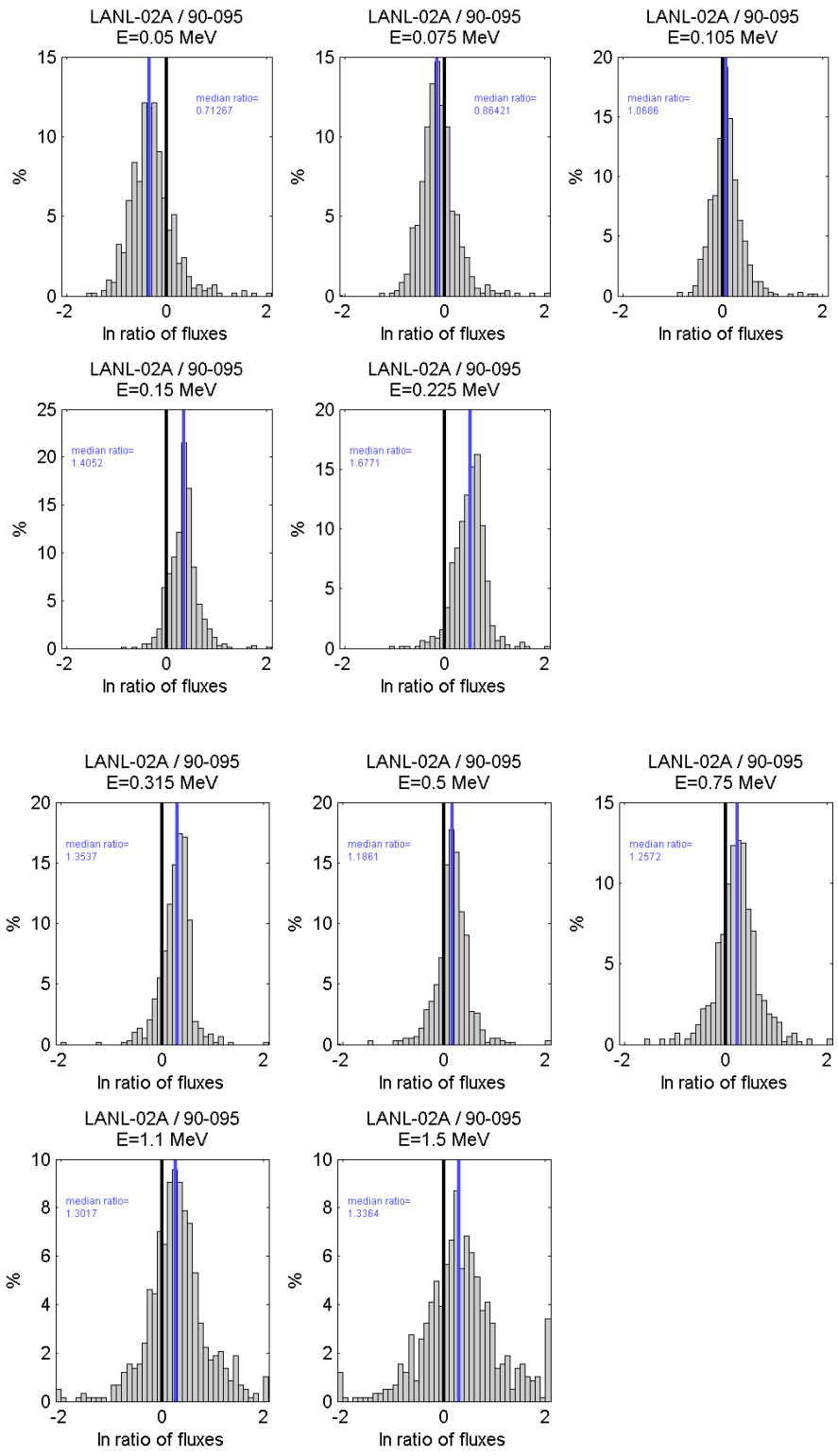

Figure A31: Histograms of flux ratios by energy channel, LANL-02A vs. 1990-095

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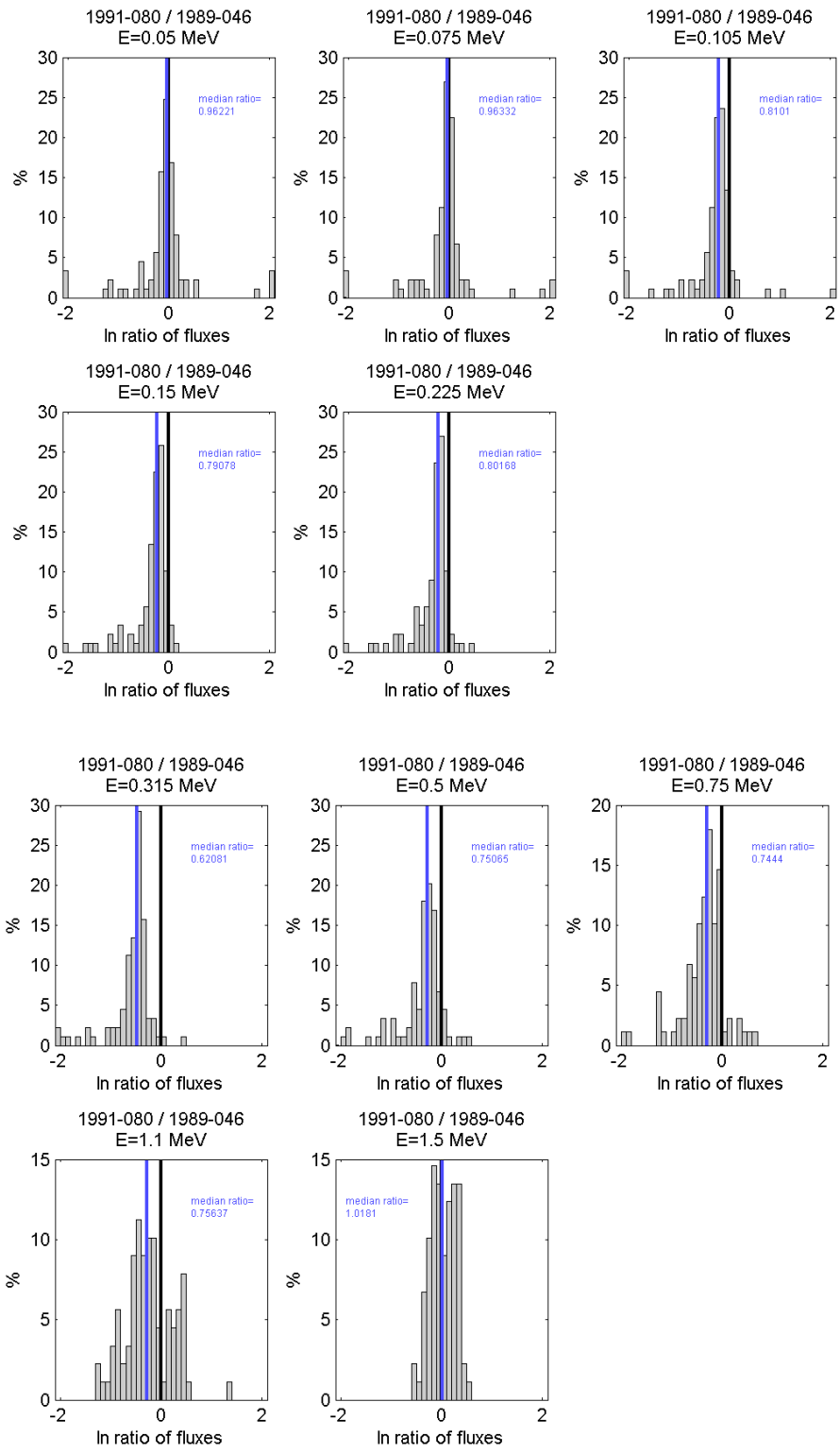

Figure A32: Histograms of flux ratios by energy channel, 1991-080 vs. 1989-046 (stated energies are for lower bound of channel)

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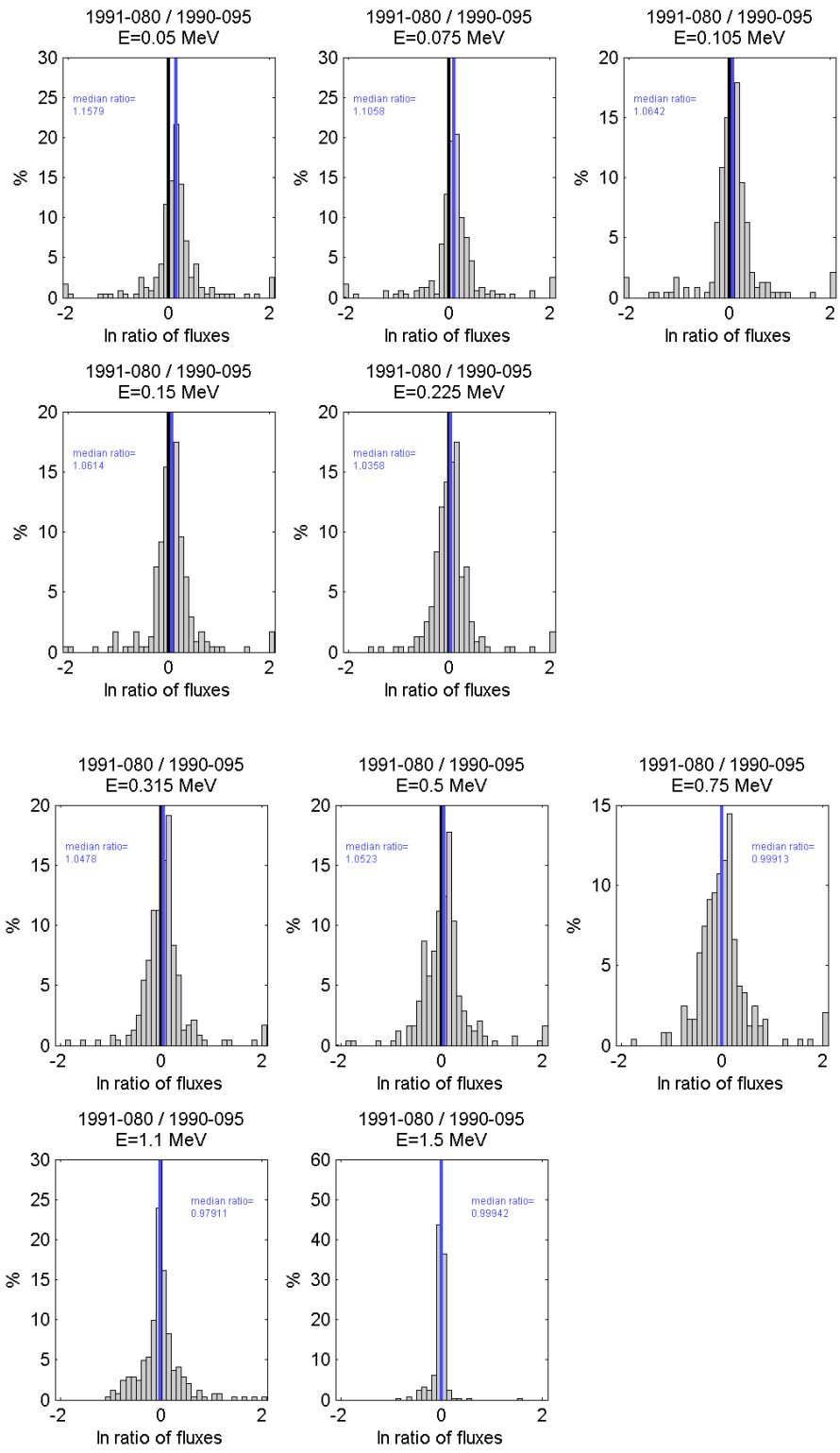

Figure A33: Histograms of flux ratios by energy channel, 1991-080 vs. 1990-095 (stated energies are for lower bound of channel)

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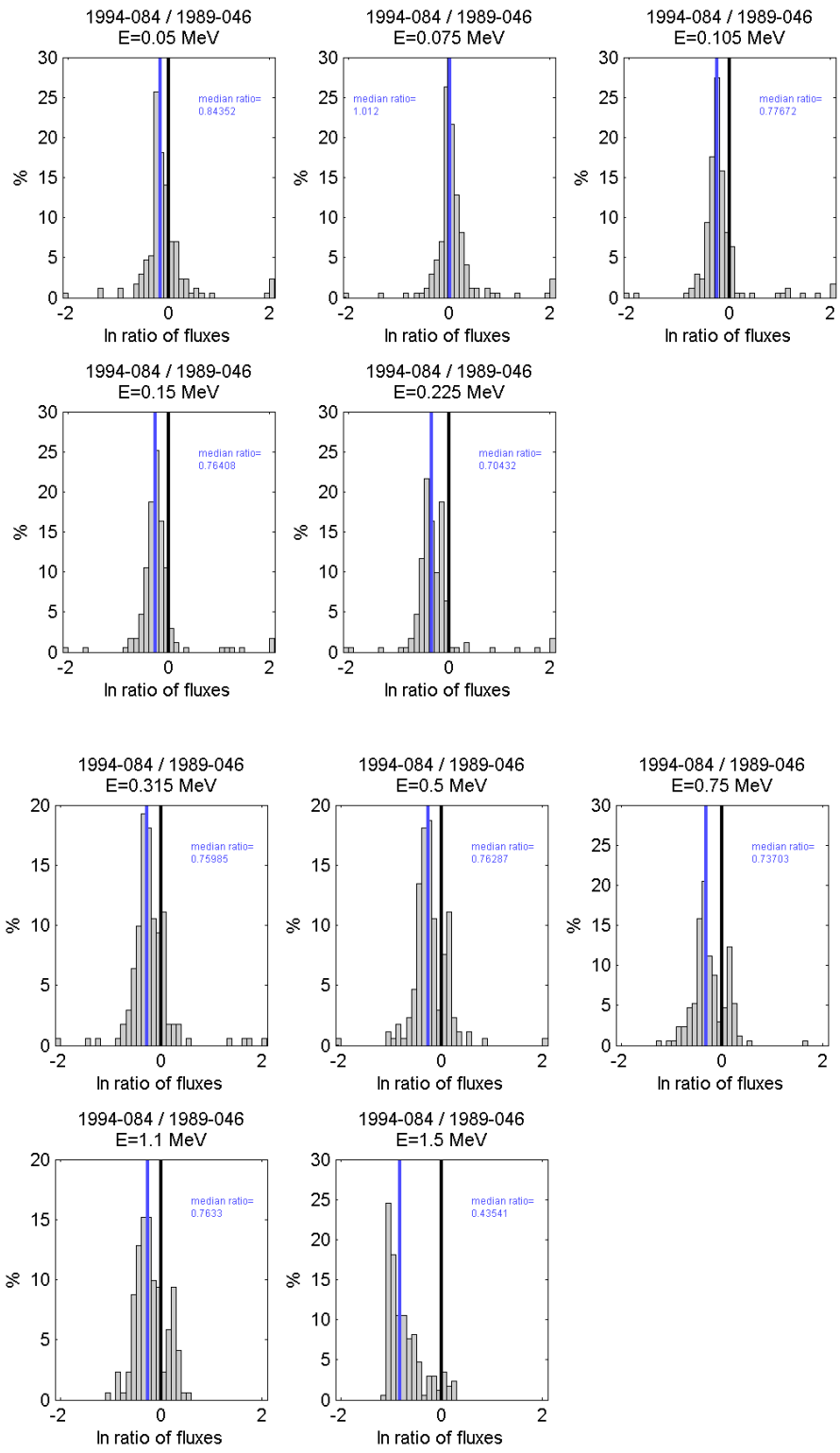

Figure A34: Histograms of flux ratios by energy channel, 1994-084 vs. 1989-046 (stated energies are for lower bound of channel)

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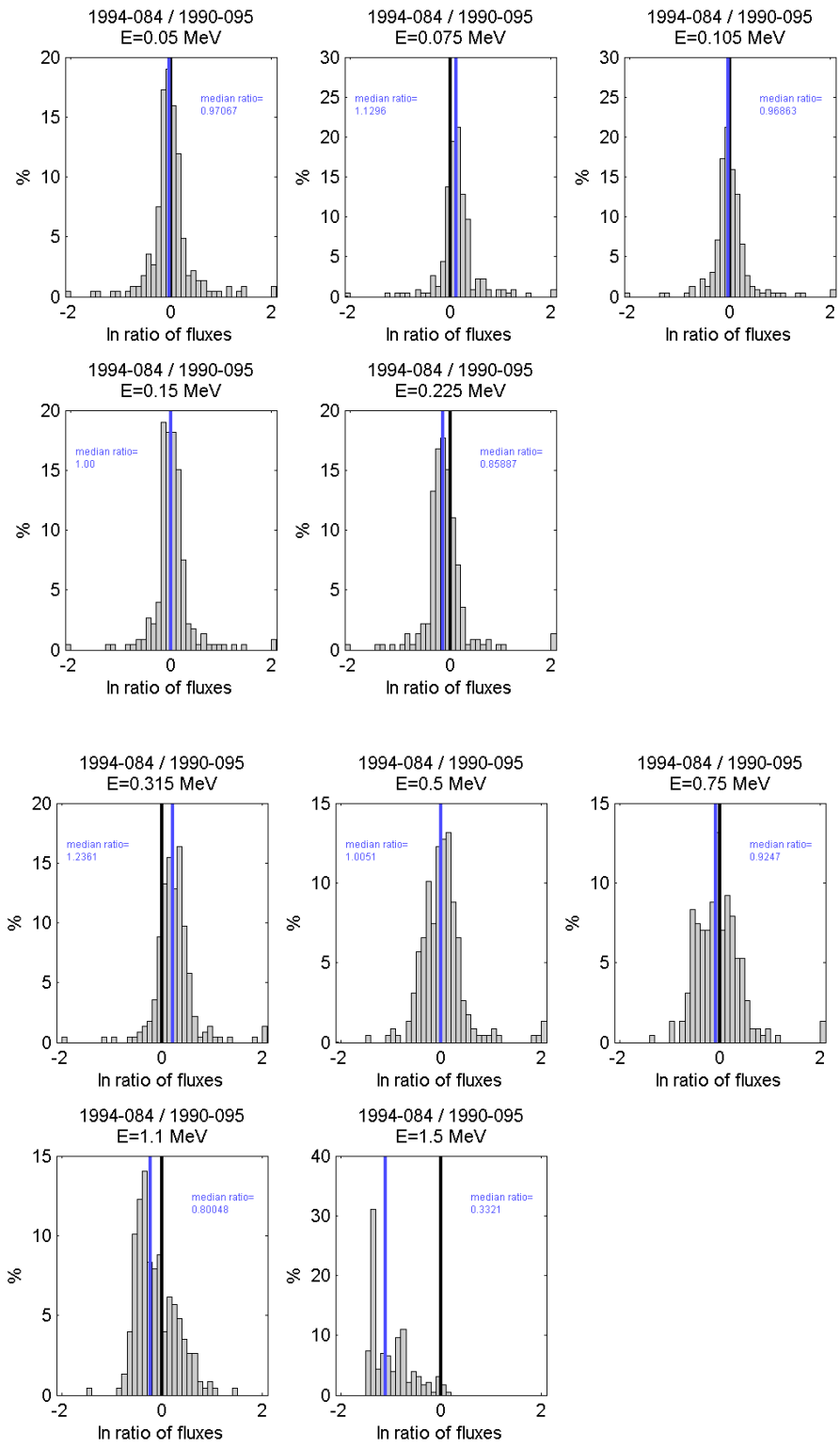

Figure A35: Histograms of flux ratios by energy channel, 1994-084 vs. 1990-095 (stated energies are for lower bound of channel)

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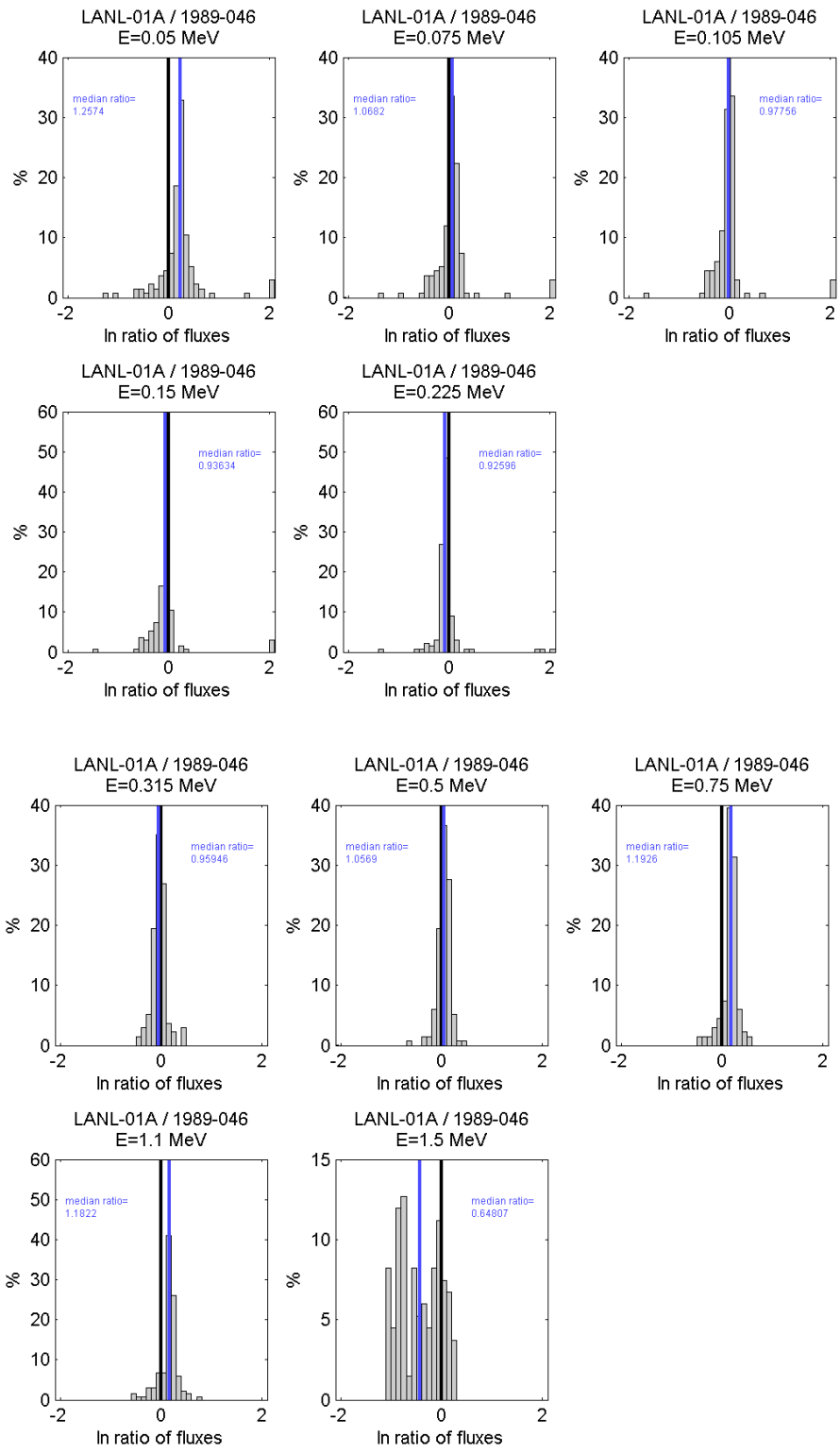

Figure A36: Histograms of flux ratios by energy channel, LANL-01A vs. 1989-046 (stated energies are for lower bound of channel)

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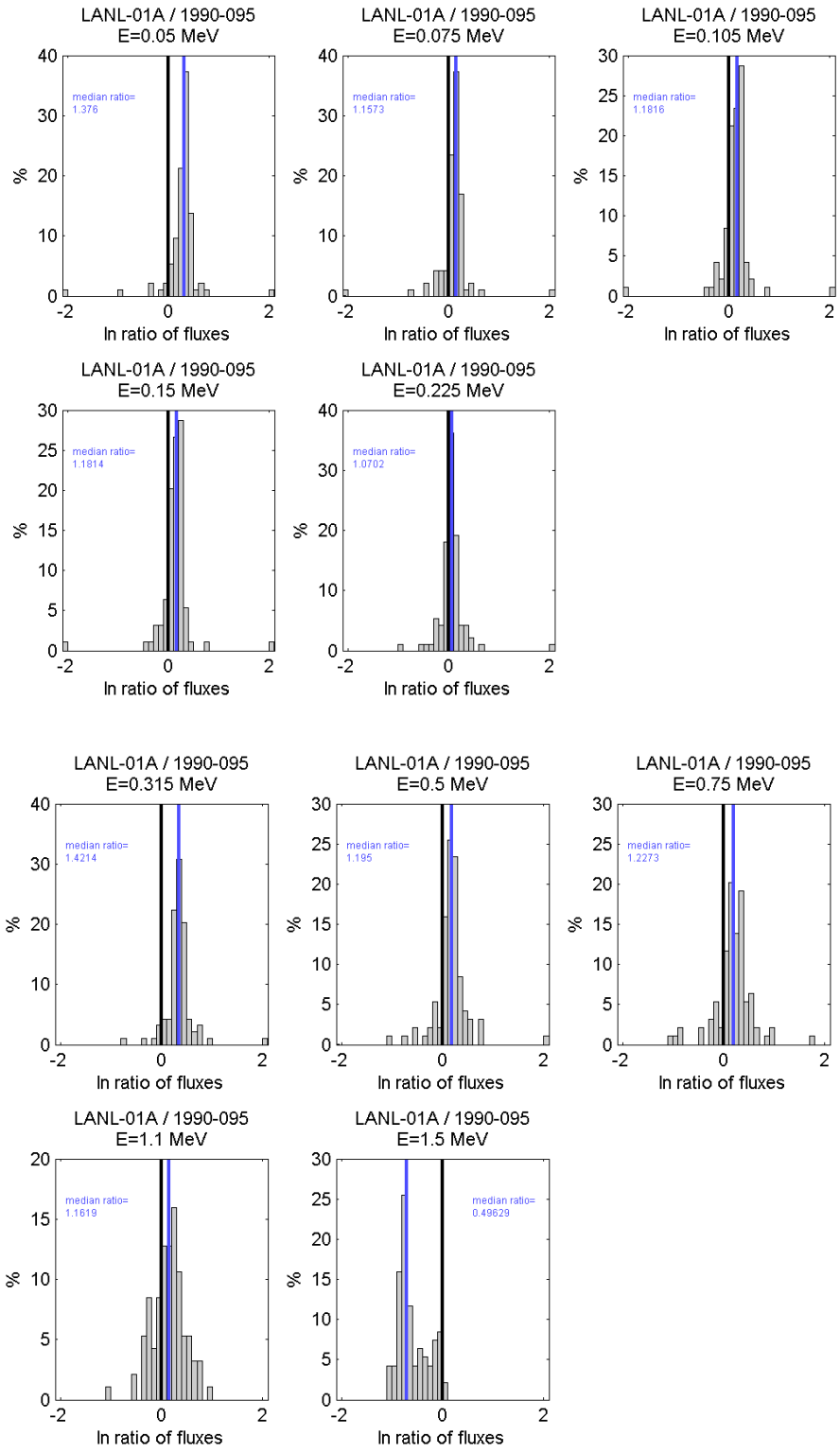

Figure A37: Histograms of flux ratios by energy channel, LANL-01A vs. 1990-095 (stated energies are for lower bound of channel)

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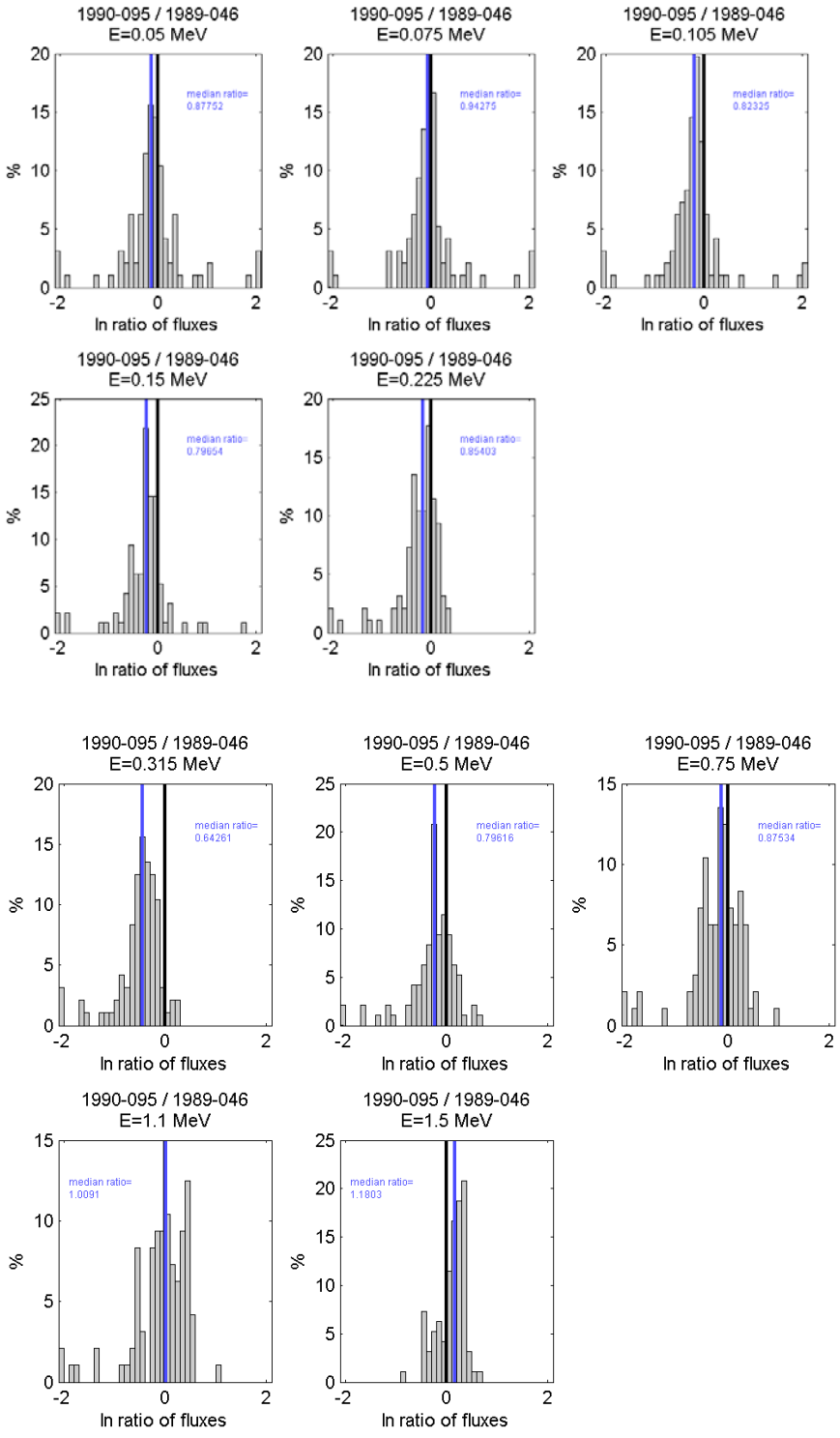

Figure A38: Histograms of flux ratios by energy channel, 1990-095 vs. 1990-095, Kp<2 last 48 hr

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APPENDIX B: CPA COMPARISONS, ADDITIONAL FIGURES

The following figures show cross calibration results for the SOPA detectors:

- Figures B1-B3: Ratio of GEO2 to GEO1 fluxes vs. channel energy. Each blue line is the ratio of fluxes vs. energy for one day; the thick black line is the median, and the two thin black lines give 2.5th and 97.5th percentiles (thus encompassing 95% of the range).
- Figures B4-B6: Histograms of flux ratios, with median offset (blue line) and notional agreement (black line).

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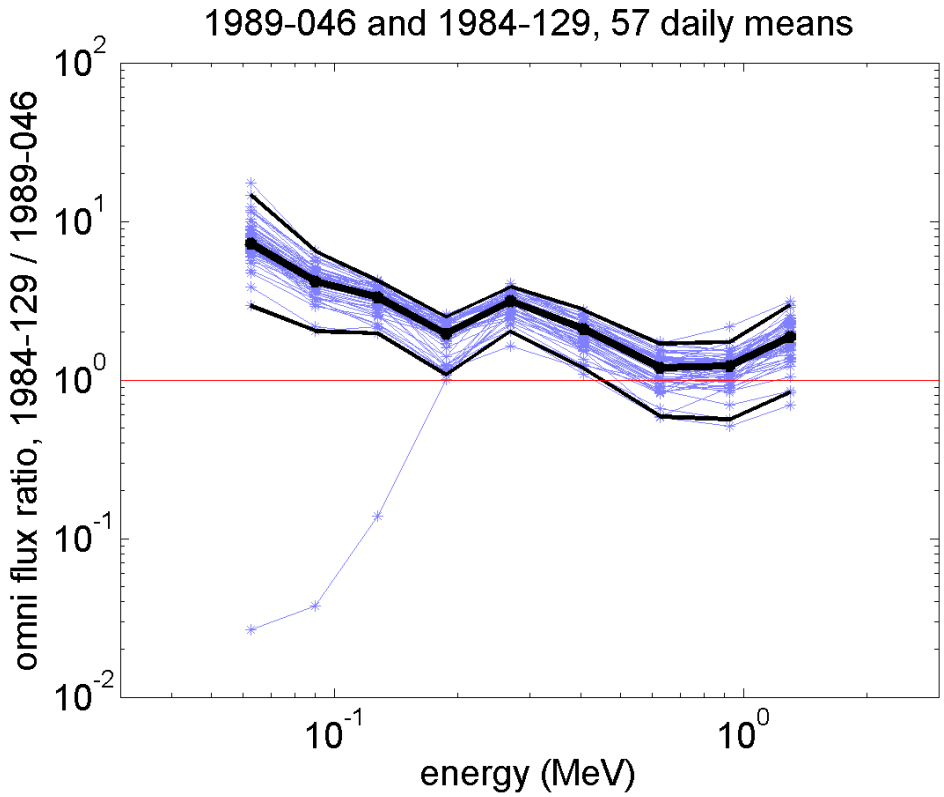

Figure B1: Flux ratios vs. channel energy, 1984-129/1989-046

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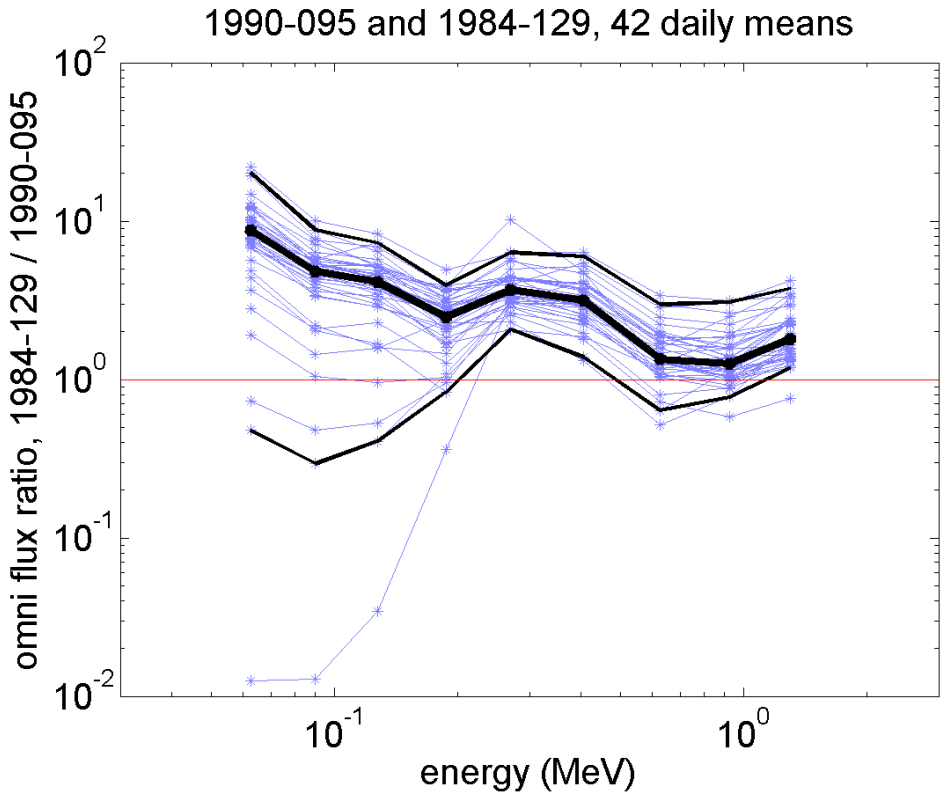

Figure B2: Flux ratios vs. channel energy, 1984-129/1990-095

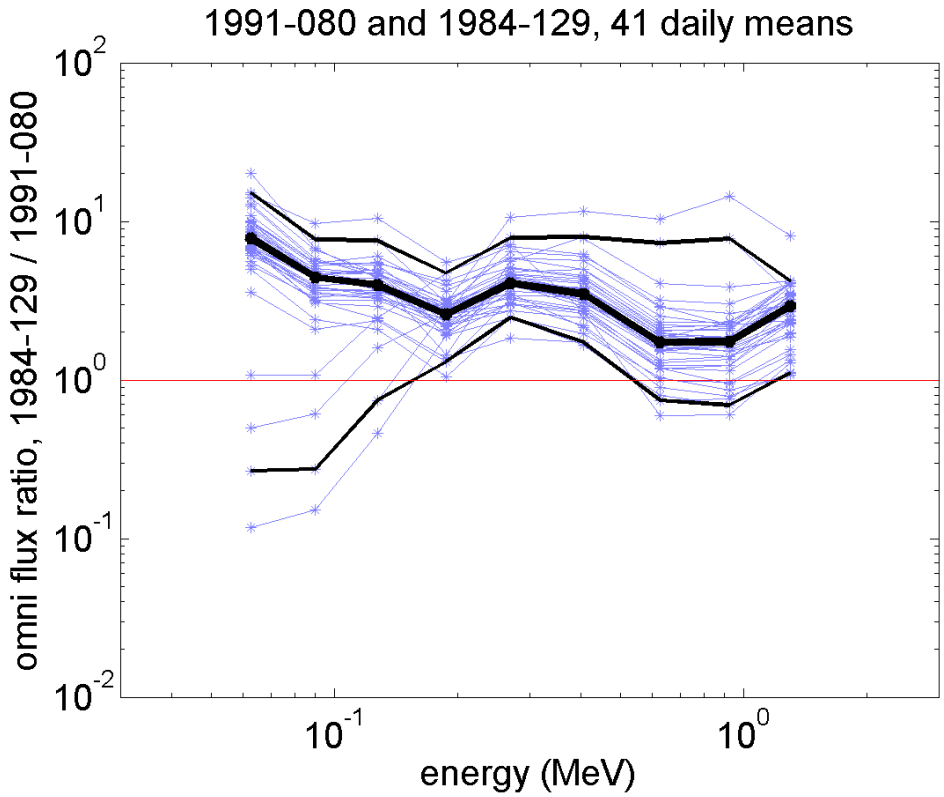

Figure B3: Flux ratios vs. channel energy, 1984-129/1991-080

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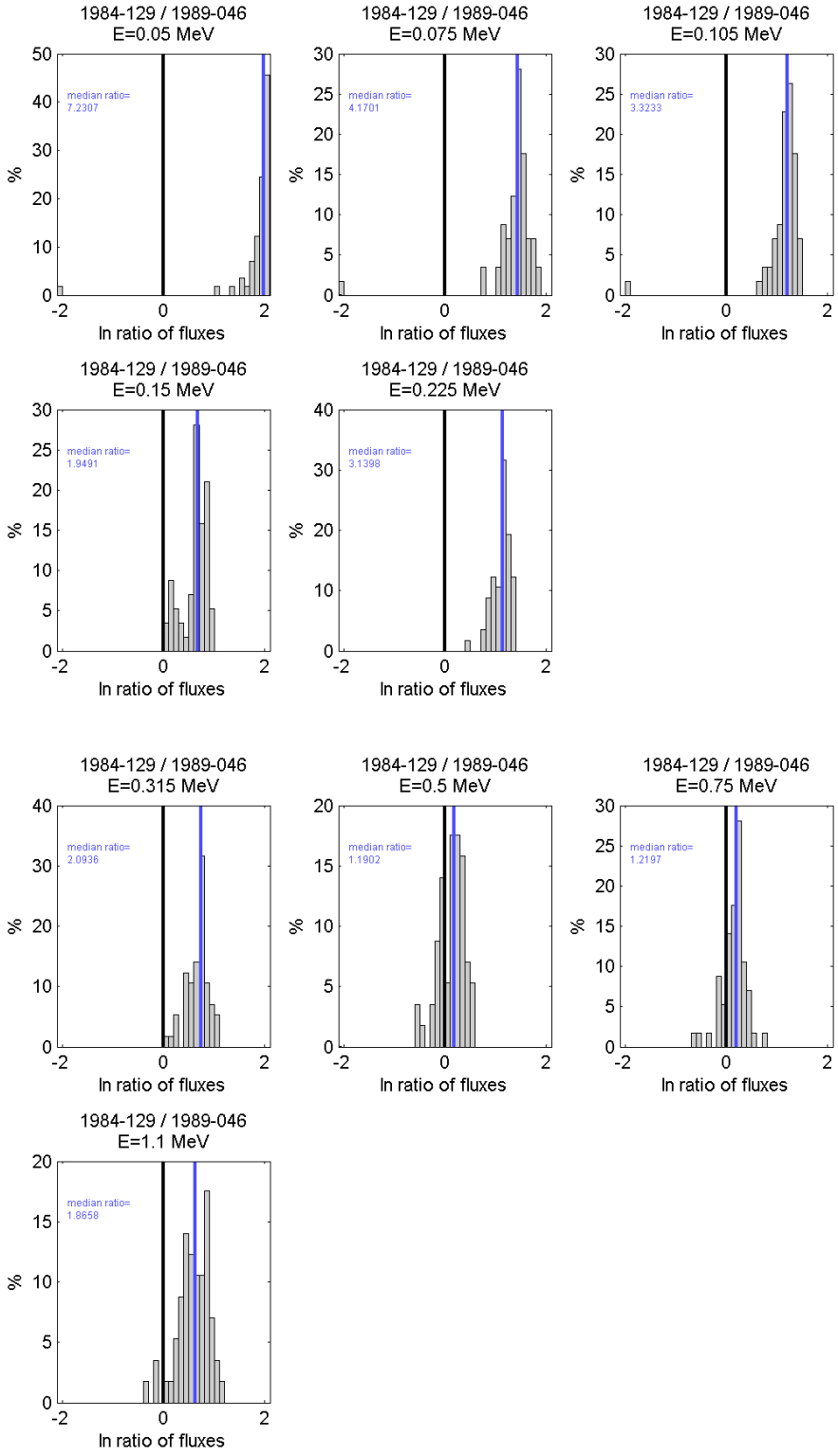

Figure B4: Histograms of flux ratios by energy channel, 1984-129 vs. 1989-046

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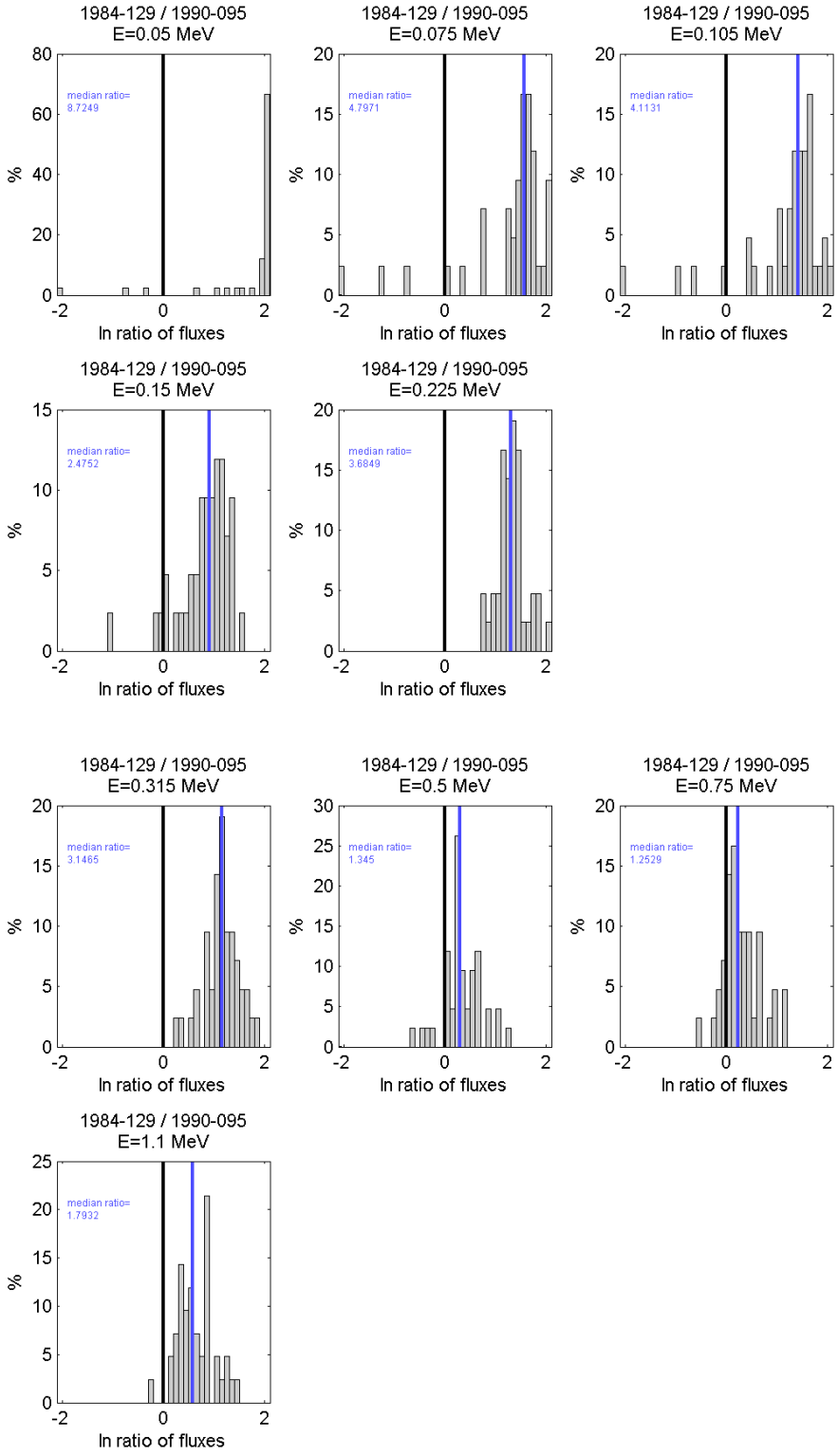

Figure B5: Histograms of flux ratios by energy channel, 1984-129 vs. 1990-095

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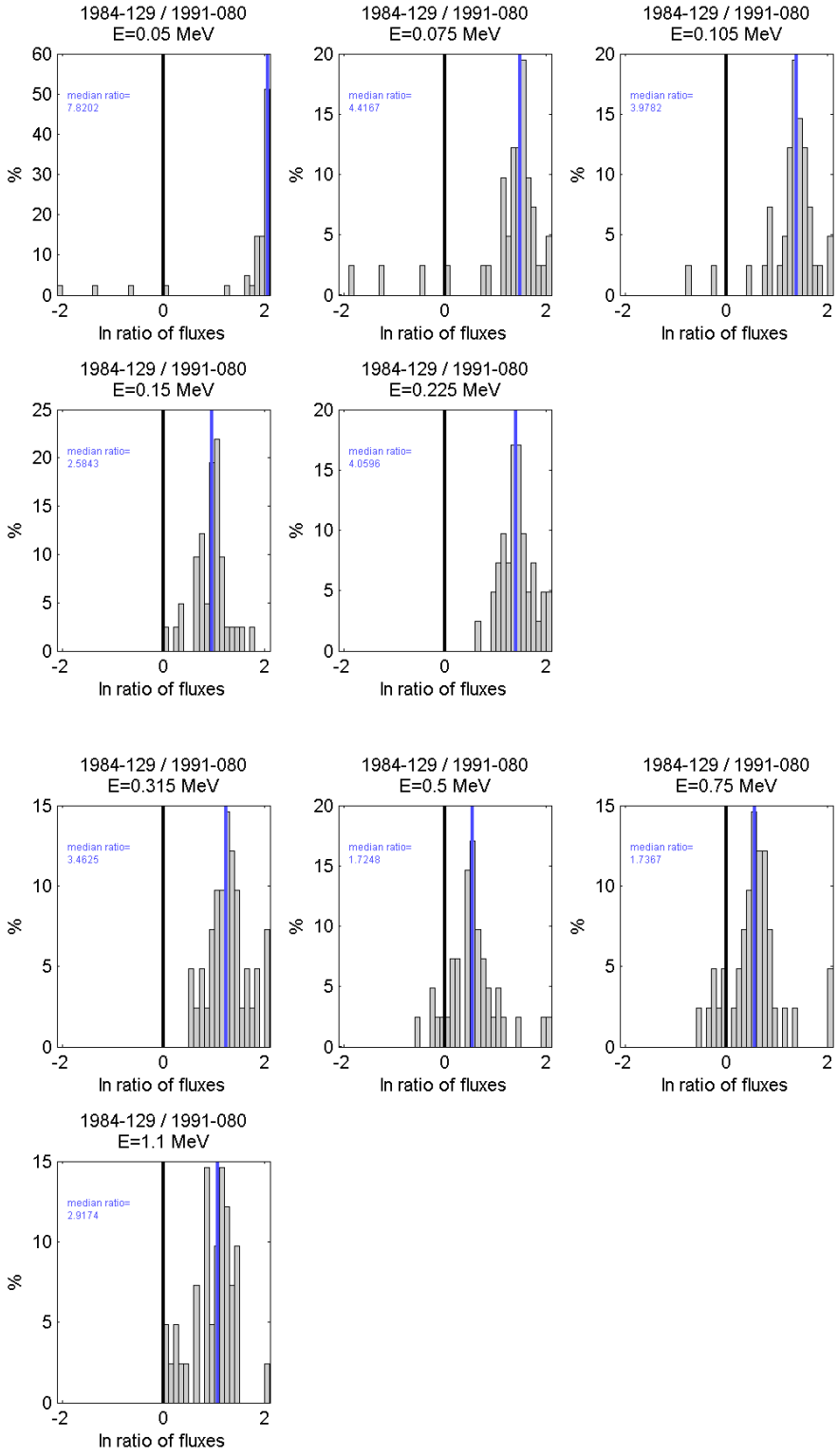

Figure B6: Histograms of flux ratios by energy channel, 1984-129 vs. 1991-080

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