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Toolkit for Updating Interplanetary Proton-Cumulated Fluence Models

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The evaluation of mission-integrated solar proton fluences in interplanetary space currently depends on statistical modeling based on energetic proton measurements recorded over a few solar cycles. Most models rely on a description of events fluence and occurrence based on a compound Poisson process for which the parameters are derived from a fit of empirical distributions of the measurements. The output is then the cumulative probability as a function of the level of fluence not to be exceeded. However, the effects of assumptions and uncertainties on the model output are in general overlooked. In this paper such effects are investigated for the well-known JPL-91 model. The use of simultaneously measured observations from different spacecraft have shown that model outputs differ mainly because of three effects: difference in calibration between the data sets, discrepancy in event selection of significant amplitudes caused by data gaps or artifacts, and separation of events into multiple events by one spacecraft but treated as one large event in the other. A complete list of solar proton event fluences from January 1974 to May 2002 is produced based on measurements from the IMP-8, GOES-7, and GOES-8 spacecraft, because calibrations between these data sets were found to be in good agreement and they cover almost three solar cycles. Artifacts caused by, for example, data errors, have been extracted after careful inspection of the list, and comparison with other available fluence data has been made to account for missed events in the data sets. The list is published to facilitate further review and future updates. An approach to generate future updates of a solar energetic particle cumulated fluence model is proposed. Related tools and data are provided.

I. Introduction

SOLAR-ENERGETIC-PARTICLE (SEP) radiation in the energy range from 1 MeV to 1 GeV has prompt and cumulative effects on technological systems such as electronic systems, detectors, and solar cells. These effects might have severe implications for spacecraft lifetime and/or performance. SEP radiation is also a limiting factor for manned missions because of high doses during transit phase or during stays on other extraterrestrial bodies. There are various sources of SEP radiation, including flares and interplanetary coronal mass ejections. The resulting flux intensification in the interplanetary medium can last several days. Individual SEP events are hard to predict deterministically because of their random nature and insufficient knowledge of the physical processes driving them, but they can a priori be treated statistically.[1–5] To avoid either costly overdesign or mission-threatening underdesign of a spacecraft, such models are used to evaluate the expected exposure from solar particle events before launch. Hence, accurate models are critical for spacecraft engineering. Statistical models are based on proton flux measurements from different experimental databases, different statistical methods, and a variety of different descriptions of the characteristics of solar energetic particles. Hence, they have various limitations related to the data quality, the statistical significance, and the hypotheses of the models. One of these effects has been studied in a recent paper[6] by assessing the impact the size of the dataset has on the predictions of the widely used JPL-91 model.[1] They show, with the use of simulated compound Poisson distributions, that in the range of relevant parameters a significant uncertainty on the fluence not to be exceeded during a mission lifetime predicted by the model is expected because of the small size of the sample of SEP events used in the model, typically 120 events. Furthermore, it was shown that the observation of an apparent stability of the model parameters with respect to the addition of a relatively small amount of data does not guarantee that the underlying model has been accurately identified.

In this paper, the stability of the fitting parameters of the underlying distribution of the SEP event fluence is investigated further on the basis of actual data. The effect of the fitting procedure, the event flux, and fluence threshold and the impact of using different data sources with different quality in terms of artifacts, gaps, and calibration errors on the same fluence prediction model output are studied. The model used is an extension of the empirical approach of Feynman et al.,[1,7] which differs only by the implementation of an automatic procedure to derive best estimates of the compound Poisson distribution function from lists of SEP events and corresponding fluence values. This study therefore allows estimates of

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some uncertainties intrinsic to the Jet Propulsion Laboratory (JPL) approach. Furthermore, it provides information on the suitability of various solar proton data sets for such modeling works. Finally, all building blocks (data set and algorithm) to generate and update a model based on the JPL approach, which minimizes the influence of data caveats, are provided.

Other modeling approaches exist, including those from King,[4] Nymmik,[3] or Xapsos.[5] Although the detailed study of these models is beyond the scope of this paper, the method of error analysis, the data quality check procedure, and the list of events attached in the Appendix are general enough to be of interest to these models as well.

This paper is organized as follows. After the introduction in Sec. I, the modeling approach and the hypothesis of the model under investigation are presented in Sec. II, and the input data used in the study are described in Sec. III. The effect of the threshold for event selection, fitting method, and data quality are studied, respectively, in Secs. IV, V, and VI. A method to update the JPL model while minimizing the source of errors is described in Sec. VII followed by the conclusion in Sec. VIII.

II. Modeling Approach and Hypotheses

In practice, the most popular approach to reproduce cumulative effects of SEP events over a long period of time (typically a mission duration of a few years) consists of using a model of the underlying probability distribution of event intensity and occurrence. The so-called JPL-91 (Ref. 1) interplanetary proton fluence model is the most widely used model of this type, and it is recommended by the European standard ECSS-10-04 (Ref. 8). It is an update of an earlier model, JPL-85 (Ref. 7). The solar proton data used in the two versions of the model are different. The JPL-85 data were collected between 1954 and 1985 from space-based instruments aboard rockets and spacecraft and from balloons and ground-based riometers during the period before the start of the space era, whereas the JPL-91 model is based only on observations from closely related instruments from 1963 to 1991 onboard interplanetary monitoring platforms (IMP) and orbital geophysical observatories spacecraft covering nearly three solar cycles (cycles 19, 20, and 21). This implies that JPL-91 consists of a more homogeneous data set. However, it contains fewer events, and the large event of November 1960 is excluded. Also, recently observed large intensity events such as the July 2000 and November 2000 are not considered in JPL-91. However, both models rely entirely on the same data processing and modeling approach, which is also applied throughout this study except for two slight differences: the calculation of solar maximum and the fitting procedure of the solar proton fluence data, which are discussed in more detail in the following.

The method of statistical analysis in the JPL models builds on King,[4] who employed a procedure developed by Burrell.[9] The model of Feynman et al.[1,7] is based on a combined consideration of 1) the distribution of fluences seen in SEP events and 2) the probability of occurrence of an event (irrespective of magnitude) over a given period. A normal probability distribution function f is employed to describe the $\log_{10}$ of individual event fluences F:

$$f(F) = (1/\sqrt{2\pi\sigma}) \exp - \tfrac{1}{2}[(F-\mu)/\sigma]^2 \qquad (1)$$

where μ and σ are, respectively, the mean and the standard deviation of the distribution of the $\log_{10}$ of fluence values.

The probability p of n events occurring in time τ is given by a Poisson distribution such that

$$p(n, w\tau) = \frac{e^{-w\tau}(w\tau)^n}{n!} \qquad (2)$$

where w is the average number of events occurring per active year.

Equations (1) and (2) are used to evaluate the expected level of the fluence that will not be exceeded during a mission at a required confidence level. In practice this is based on the determination of the quantile q_x of a cumulated $\log_{10}$-normal fluence distribution P. The quantile q_x is the value of the fluence such that the probability of the fluence being below this value is equal to x. The corresponding probability is also called the confidence level. The probability P of exceeding a selected fluence level F during a mission lifetime τ can be expressed analytically as

$$P(>F, \tau) = \sum_{n=1}^{x} p(n, w\tau) Q(F, n) \qquad (3)$$

where $Q(F, n)$ is the probability that the sum of all fluences caused by $n(n = [1, \infty])$ events will exceed 10^F. The derivation of q_x requires an estimate of the parameters w, μ, and σ to perform computer based Monte Carlo simulations using Eq. (1) to derive $Q(F, n)$. The complete model has been coded, and the source code can be found in Appendix B (based on the algorithm described in Feynman et al.[7]). The parameters μ, σ, and w of the model are estimated from the data as described next.

The estimates of the fitting parameters can be expected to depend of the phase of the solar cycle because a majority of all SEP events occur during solar active periods. Feynman et al.[7] noted that the solar cycle could be divided into a high-fluence active sun period of seven years and a low-fluence quiet sun period of four years when the probability of significant cumulated fluence from SEPs could be neglected. Consequently, the proton events used in JPL-91 model are those occurring during the seven active years (two years before the solar maximum and four years after solar maximum) of the three solar cycles. The SEP events are assumed to have an equal probability of occurrence over this interval. Solar maximum was considered to occur at the maximum of the 13-month running average value of the international sunspot number. As a first approximation, the fitting parameters obtained next are assumed to be constant over the seven active years. The proton events considered are described by the total fluence over a series of days during which the daily average proton flux for particles with energy >10 MeV exceeded a flux threshold of one particle $cm^{-2}\ sr^{-1}\ s^{-1}$. An event is assumed to begin when the daily average flux exceeds the threshold and assumed to end when the average flux falls below the flux threshold for two consecutive days. As a result multiple events may be treated as one single event. The time of an event is defined as the first day when the average flux exceeded the threshold value. A fluence threshold of $10^7\ cm^{-2}$ was employed for the >10-MeV particles; for other energies other fluence thresholds would apply. The estimate of w is simply the observed average number of events per year over solar active years.

The dates of solar maximum used in this paper differ slightly from the values used by Feynman et al.[1,7] In this paper the various dates of solar maximum (Nov. 1968, Dec. 1979, Sept. 1989, and April 2000 for solar cycles 20, 21, 22, and 23, respectively) are derived from the 13-month running mean international sunspot number from the World Data Center for the Sunspot Index (SIDC) and are slightly different from the values used in JPL-91, which were based on preliminary estimates.[7]

The parameters μ and σ can be determined from the empirical fit of the distribution function of the $\log_{10}$ of the fluence of events by plotting the $\log_{10}$ of the fluence data on a normal probability paper. A normal distribution appears as a straight line on such a plot. Feynman et al.[1] noted that only the high-intensity part of the empirical distribution function can be well fitted by a $\log_{10}$-normal law because the lower intensity events are much more numerous than would be predicted by a $\log_{10}$-normal distribution. They also noted, however, that the impact on the model predictions of high fluence level (say, typically above 80% confidence level) is marginally depending on the lower intensity part. Because engineers are usually interested in confidence levels above 80% in using such models, μ and σ can be estimated from the upper part of the distribution for a wide range of engineering applications. Feynman et al.[1,10] performed an empirical fit of the upper part of the distribution. In this study, the same graphical method is used except that the empirical fit is replaced by a least-squares fitting technique of the second half of the distribution (above the median). The advantage with these specifications is that the curve fitting is easily reproducible, and therefore the impact on model output caused by differences between various data sets can be objectively assessed.

With the preceding described approach a broad range of effects can significantly modify model prediction. The possible effects include 1) event selection criteria (grouping of events), 2) the choice of flux threshold for event identification, 3) the choice of fluence threshold for event identification, 4) the identification of the high activity part of the solar cycle, 5) parameter fitting procedure of the event intensity distribution, 6) size of the dataset, 7) calibration uncertainty, 8) data gaps, and 9) data errors. In the following, the impact of the fitting procedure, the event flux, and fluence threshold and the use of different data sources (data gaps, data errors, and calibration) on model output is investigated.

III. Data Sets

The newly developed Space Environment and Data Analysis Tool (SEDAT) system[11] based on ESA specifications[12] allows storage of data in an arbitrary format to be analyzed with a combination of the front-end data query and other processing tools. SEDAT was used to produce lists of daily averaged solar proton fluences from different instruments in order to investigate model stability with respect to variations in actual data. The current study is based on proton flux values integrated over the energy range above 10 MeV. The data are essentially the ones measured by instruments onboard the IMP-8 and GOES spacecraft. A short description of the specific properties and related processing of the various data sets is given next. The relative periods of time covered by the various data sets are schematically represented in Fig. 1.

The data from the series of GOES-6, -7, -8, and -10 as measured by the energetic particle sensor (EPS) included in the space environment monitor instrument package are provided by the National Geophysical Data Center from the National Oceanic and Atmospheric Administration. Small data gaps in GOES data were filled by the geometric mean of the six closest data points. To eliminate occasional single data errors and to reduce the noise level, a median smoothing technique has been adopted as suggested by Hapgood.[13] The running median flux is calculated within a time window of $\delta t = 4$ h, that is, the median of the set of flux values within a window of width δt centered at time t. The 5-min smoothed GOES data were then converted to daily averages by integrating the 5-min smoothed average flux to daily averaged fluence.

Recently it was discovered that the GOES-10 energetic proton detectors were showing intermittent, high noise levels in the higher-energy proton channels (greater than about 80 MeV) first noticed in data taken during April 2003 [compare GOES Satellite Reports from the Space Environment Center (SEC)]. Similar problems were experienced on the P6 and P7 particle channels on the GOES-12 EPS Dome detector prior to their failure earlier this year (compare SEC GOES Satellite Report). The loss of data from the P6 and P7 channels significantly impacts the integral proton flux products above about 10 MeV (e.g., >10, >50, and >100 MeV). However, this study does not cover observations beyond July 2002.

The charged particle measurements experiment (CPME) solar proton monitor data, designed and built at the Applied Physics Laboratory, on IMP-8 are provided by National Space Science Data Center OMNIWeb. It is one of the main sources of data used to build the JPL-91 model. The IMP-8 data are hourly averaged integral fluxes for particles in this energy range. In this study, to mitigate the influence of the rather large data gaps the hourly averaged data were converted to daily averaged data by taking the arithmetic average of the existing data for that day, which in turn were converted to the daily fluence. Several caveats of the CPME data have been identified. A comparison with GOES data suggests that the CPME instruments might have significant, uncorrected dead-time effects, especially for the largest events.[14] Furthermore, from inspections of the data it is also evident that this instrument suffers from high intrinsic background levels, which make it difficult to extract small events.

The Goddard medium-energy (GME) data from Goddard Space Flight Center are provided by the Web site of the Coordinated Data Analysis Workshop (CDAW) as differential flux values for given energy channels. The differential flux was integrated from 10 to 385 MeV assuming an exponential in rigidity fit. An exponential interpolation with an e-folding time of 2 h was adopted to fill the rather large data gaps found in this data set, and the running median was calculated to reduce data spikes, whereas the fluence values could then be obtained by simple time integration.

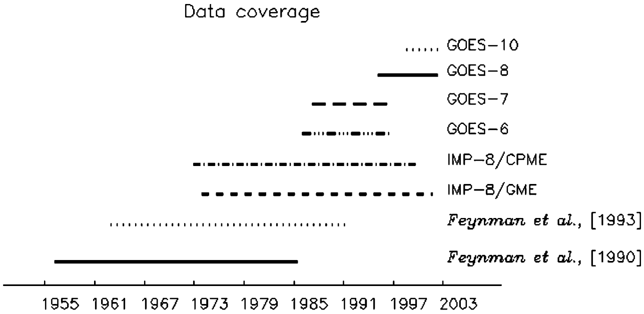

Fig. 1 Schematic of the time period covered by the spacecraft/instruments used in this study.

IV. Effect of Threshold

When all data sets have been converted to daily averaged fluence time series, the same method as the one described by Feynman et al.[1,7] (see Sec. II) can be applied to identify and select solar proton events and determine the corresponding fluence. The critical parameter, which determines the number and the size of the events, is the threshold above which events are selected. The influence of the value of the threshold is investigated in this section on the basis of the event list for the period 1956–1985 published by Feynman et al.[7] The parameter estimate analysis was performed for each of a series of successive fluence threshold values, 10^X cm^{-2} with X ranging from 6 to 7.5, and the results are displayed in the first three panels in Fig. 2 for the parameters μ, σ, and w, respectively.

In the last panel the corresponding effect on the 90th and 95th quantiles is shown. It can be seen that the model parameters can vary by more than 20% over the range of threshold values. However, the resulting overall effect on the model prediction as measured by the quantile is at most of the order of 20% on the 90th quantile and up to 50% on the 95th quantile. This moderate impact of the choice of the fluence threshold on model output is because the most significant contribution to the high values of the quantiles is from the higher intensity part of the distribution, which does not depend much on the threshold value, as already noted by Feynman et al.[1] A similar study on the effect of the flux threshold (compare definition in Sec. II) to be exceeded for event selection was performed for various different thresholds (1, 2, 5, and 10 particles cm^{-2} sr^{-1} s^{-1}), but it was found to have a negligible or no impact on the quantile estimates because the peak flux is generally several orders of magnitude larger than the background. However, the flux threshold can potentially have an indirect impact on the model through the event selection criteria. The differences between two datasets can lead to a different treatment of individual events, for example, by the division of one large event in one data set into multiple events in the other. This aspect is investigated further in Sec. VI.

Because the threshold values were found to have only moderate direct impact on model output for high-level quantiles (around the 80th quantile and above), a fluence threshold of 10^7 cm^{-2} and a flux threshold of 1 particle cm^{-2} sr^{-1} s^{-1} are used (as was done by Feynman et al.[1]) for the selection of events throughout the rest of this study. The number of events identified from the different spacecraft and the time range of the observation are shown in Table 1.

V. Comparison Between JPL-91 and JPL-85 Models

In this section the effect of using two different data sets as input to the same model generation procedure is illustrated with the

Table 1 Number of events identified for the different data sets loaded in SEDAT

Data source	Time period (mm/dd/yy)	No. of events
IMP-8/GME	01/01/1974–10/26/2001	189
IMP-8/CPME	01/01/1973–01/01/2000	219
GOES-6	01/01/1986–11/30/1994	59
GOES-7	04/01/1987–04/01/1996	70
GOES-8	03/01/1995–06/17/2002	50
GOES-10	08/01/1998–07/01/2002	39

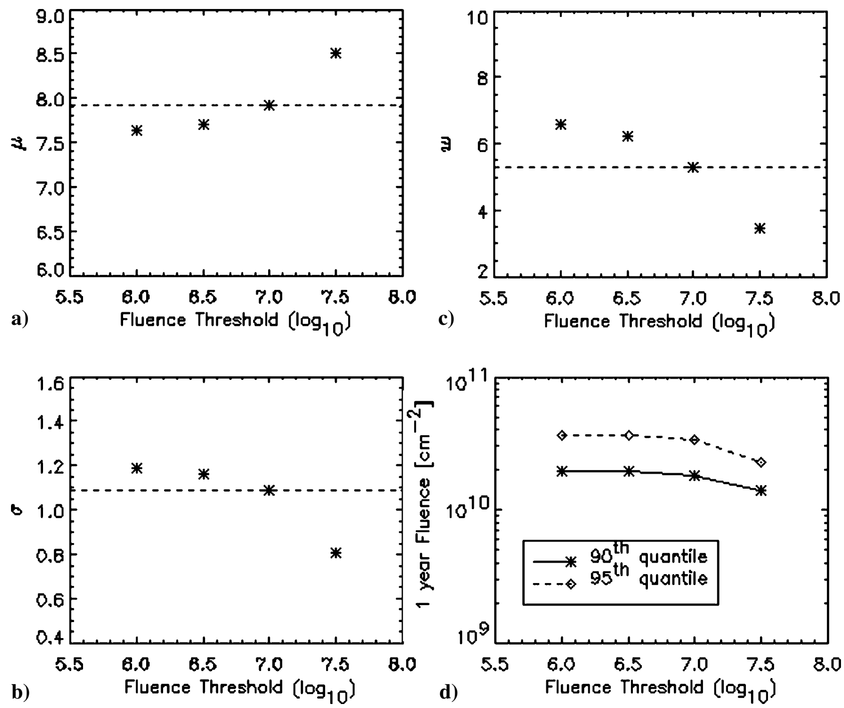

Fig. 2 Dispersion of the parameters a) μ, b) σ, c) w, and d) of the 90th and 95th quantile as a function of the fluence threshold.

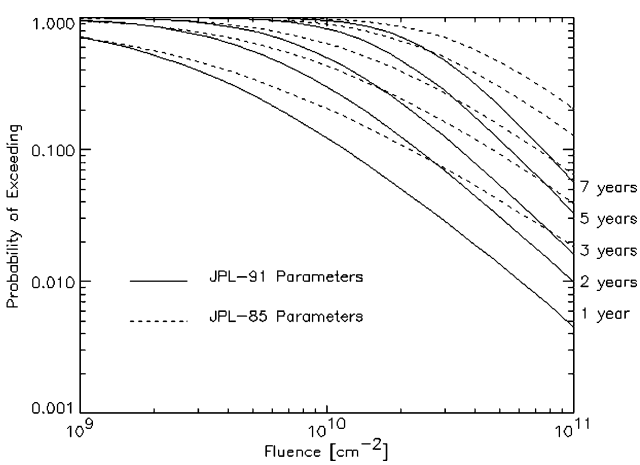

Fig. 3 Comparison of the JPL-85 model and the JPL-91 model predicted probability of exceeding selected fluences of protons with kinetic energy >10 MeV for periods of exposure ranging from one to seven years.

example of the two versions of the JPL model, JPL-85 and JPL-91. A comparison between the predictions of JPL-85 and JPL-91 for protons >10 MeV is shown in Fig. 3. It can be seen that the differences between the two models are very strong for the high quantile values (more than a factor 2 for the 90th quantile). Because the same mathematical procedure was used for generating these models, this difference is entirely caused by the differences between the fitting parameters w, μ, and σ estimated by Feynman et al.[1,7] The reason for such differences is investigated in this section.

Because of the unavailability of the list of events used to build the JPL-91 model, an equivalent list is reconstructed in the following to allow comparison with the earlier model and future updated ones. As just mentioned, the JPL-91 list made use of data from IMP-8/CPME and other spacecraft. The IMP-8 data are available from day 192 of 1985 to day 126 of 1991 in the period encompassed by the JPL-91 model. This was used to determine a list of events in this period. For the period from day 331 of 1963 to day 192 of 1985, the events published by Feynman et al.[7] have been used. The resulting list is considered to correspond closely to the actual JPL-91 list of events because the instrument used and event selection procedure are as identical as what can possibly be done based on the information provided by Feynman et al.,[1,7,10] except for the slight difference in the date of solar maximum (see Sec. II).

Table 2 Fitting parameters (energy >10 MeV)

	1963–1991		1956–1985	
Parameter	This paper	JPL-91	This paper	JPL-85
w	6.3	6.75	5.6	5.8
$\mu(\mathrm{alog}_{10})$	7.79	7.86	7.94	7.89
$\sigma(\mathrm{alog}_{10})$	1.07	0.97	1.07	1.125

The parameters derived from the two data sets respectively for the period 1963–1991 and 1956–1985 for particles with kinetic energy >10 MeV are shown in Table 2 together with the parameters estimated by Feynman et al.[1,7] for the same periods. Also, the corresponding plots of the intensity occurrence on normal paper are shown in Fig. 4, and the plots of the resulting model estimates of the probability of exceeding a given fluence over one year are shown in Fig. 5. The discrepancies between the average number of events per year w as observed by Feynman et al.[1,7] and in this paper are caused by the slightly different determination of solar maximum (see Sec. II). However, the relatively small differences in w do not significantly affect the final model predictions.

Figure 5 shows that the modeling approach of this study leads to closer model outputs (about 25% discrepancy on the 95th quantiles) when applied to the two different lists of events just described (1956–1985 and 1963–1991) than the approach by Feynman et al.,[1,7] which lead to the rather large difference between JPL-85 and JPL-91 (more than a factor 2 discrepancy on the 95th quantiles). The difference between estimates based on nearly identical dataset (especially the period 1956–1985) can be explained by the different hypotheses used to determine the best fit but can also be caused by differences in data processing (especially for the 1963–1991 list). Feynman et al.[1,7] were looking for an empirical fit of the higher-intensity part of the distribution function, which was considered as a good compromise between the need to obtain a rather conservative estimate of the fluence and the need to account for most of the distribution function. As described in Sec. II, we have chosen to use an objective method consisting of fitting the upper half above the

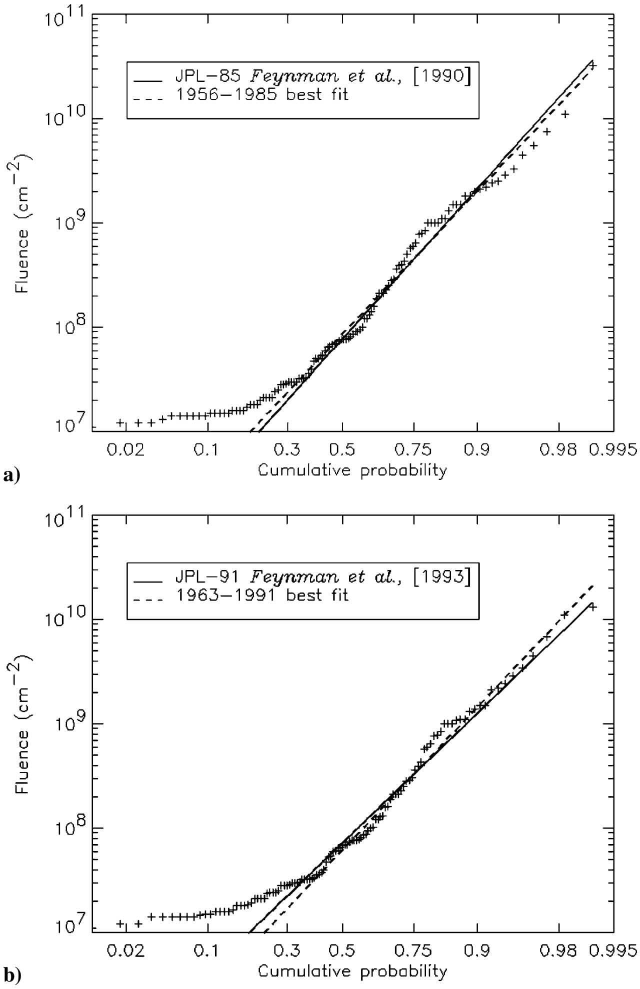

Fig. 4 The $\log_{10}$ of the event fluence distribution for proton above 10 MeV on a normal probability plot for a) the 1956–1985 event list and b) the list of events corresponding to the period 1963–1991: – – –, best fit of the upper half of the distribution and ——, fits of Feynman et al.[1,7]

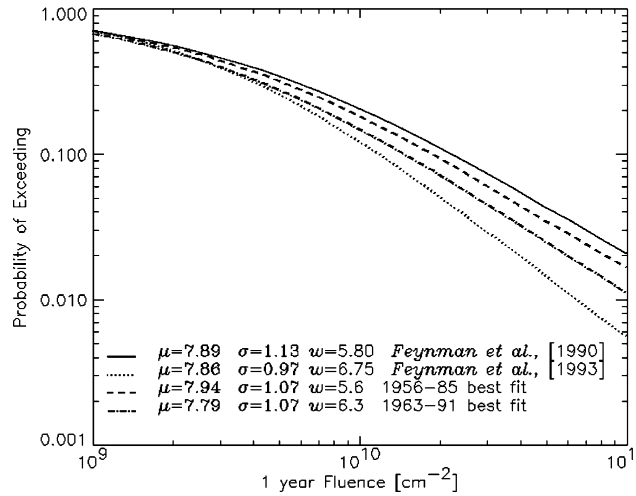

Fig. 5 Examples of fluence probability curves for a one-year mission and for proton with energy above 10 MeV calculated with the two different fits of the 1956–1985 and 1963–1991 event lists.

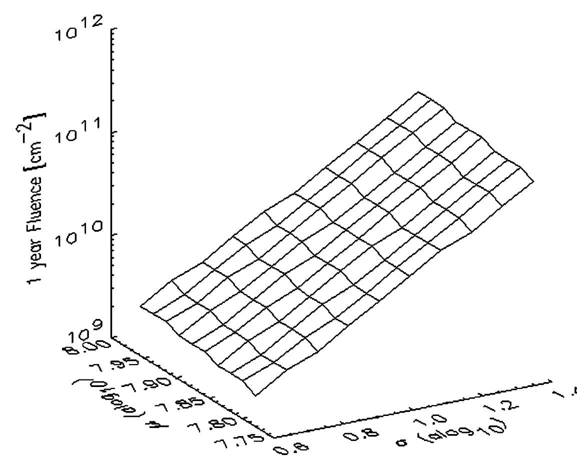

Fig. 6 Sensitivity test of the parameters μ and σ on the prediction of the 90th quantile for a one-year mission.

median with a least-squares best-fit technique. The small remaining difference (less than 50% on the 90th quantile) of the model output, when employing this technique, can be either caused by the natural statistical variation related to the finite size of the data set[6] or caused by the uncertainty of the ground based measurements prior to 1963 (compare Secs. II and VII.A).

Although the difference between the parameter estimates made in this paper and the ones made by Feynman et al.[1,7] are small (less than 10%), they can lead to significant change of the fluence predicted by the models. A sensitivity analysis of the 90th quantile on μ and σ has been performed and is shown in Fig. 6. The steeper incline of the surface in the σ axis suggests that most of the variation of the fluence predicted by the various models is caused by differences in the value of σ.

VI. Discrepancies and Cross Calibration Between Data Sets

In this section, the event lists from each instrument (see Table 1) are compared with each other, and the effect induced on the final model output by the differences in these data sets is investigated. For each set of spacecraft instruments that operate within the same time period, the event fluences observed simultaneously by both spacecraft (of the accuracy of ± 2 days in the start and end date) have been plotted against each other on a log-log plot. If an event observed in one data set appeared as multiple events in another data set, they were not considered to be the same event and hence not considered in the cross-calibration analysis. Cross calibration between two data sets is made by fitting with a least-squares technique the logarithms of the fluences of one data set as a function of the other:

$$\log(F_1) = l + d \cdot \log(F_2) \tag{4}$$

where l is the intercept on the y axis and d is the slope of the straight line and F_1 and F_2 stand for the two data set fluence values. The results for all instrument overlaps are given in Table 3, where the derived values of l and d for the 11 cases are given together with the event discrepancy between the different sources (the events observed in one source but not the other and vice versa). A few graphical illustrations of the fit are also given on Fig. 7. Well-correlated data sources should have a slope near unity and an intercept near zero as the straight line shown in Fig. 7. The advantage of performing the cross calibration at high level (i.e., directly on the integrated fluence) rather than at the instrument response level are twofold: first it provides information directly relevant to the model comparisons, and second it is less sensitive to local effects on instruments (e.g., contamination of measurements by MeV electrons at geosynchronous orbit).

The cross-calibration results in Table 3 and Fig. 7d show large discrepancies between GOES-6 and GOES-7, the latter returning higher fluence values in all events (about a factor 2 on average). Also, observations from GOES-8 are systematically (about a factor 2 on average) higher than those measured by GOES-10 (Fig. 7i). Comparisons of the IMP-8 observations from the GME and CPME instruments reveal that GOES-6 and GOES-10 fluences (Figs. 7b, 7c, 6j, and 6k) are systematically lower (except for the largest events in GOES-10), whereas they compare rather well with GOES-7 and GOES-8 measurements (Figs. 7e, 7f, 6g, and 6h).

Table 3 Cross-calibration results for solar proton event datasets

Data source 1	Not seen in 2	Data source 2	Not seen in 1	Intercept (l)	Slope (d) [$\log_{10}$]
IMP-8/GME	14	IMP-8/CPME	54	−0.29	1.04
IMP-8/GME	21	GOES-6	13	1.16	0.90
IMP-8/CPME	35	GOES-6	12	1.35	0.87
GOES-7	20	GOES-6	11	0.68	0.96
IMP-8/GME	6	GOES-7	7	0.47	0.94
IMP-8/CPME	24	GOES-7	10	0.95	0.88
GOES-8	5	IMP-8/GME	1	−0.05	1.02
GOES-8	3	IMP-8/CPME	17	−0.35	1.06
GOES-8	12	GOES-10	6	0.94	0.92
IMP-8/GME	6	GOES-10	5	1.32	0.86
IMP-8/CPME	16	GOES-10	1	1.71	0.81

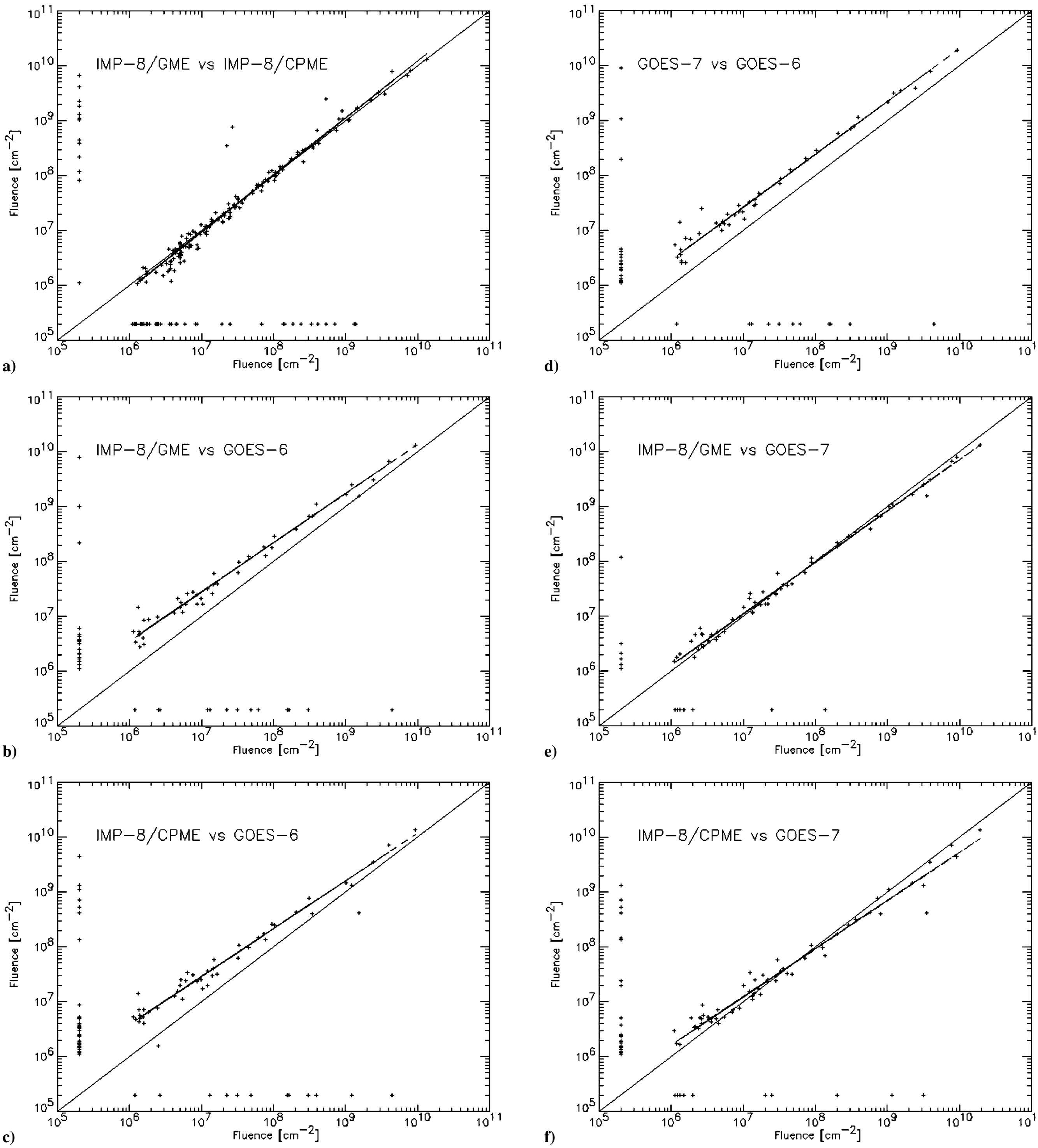

Fig. 7 Intercalibration of event fluences measured by different instruments operating simultaneously.

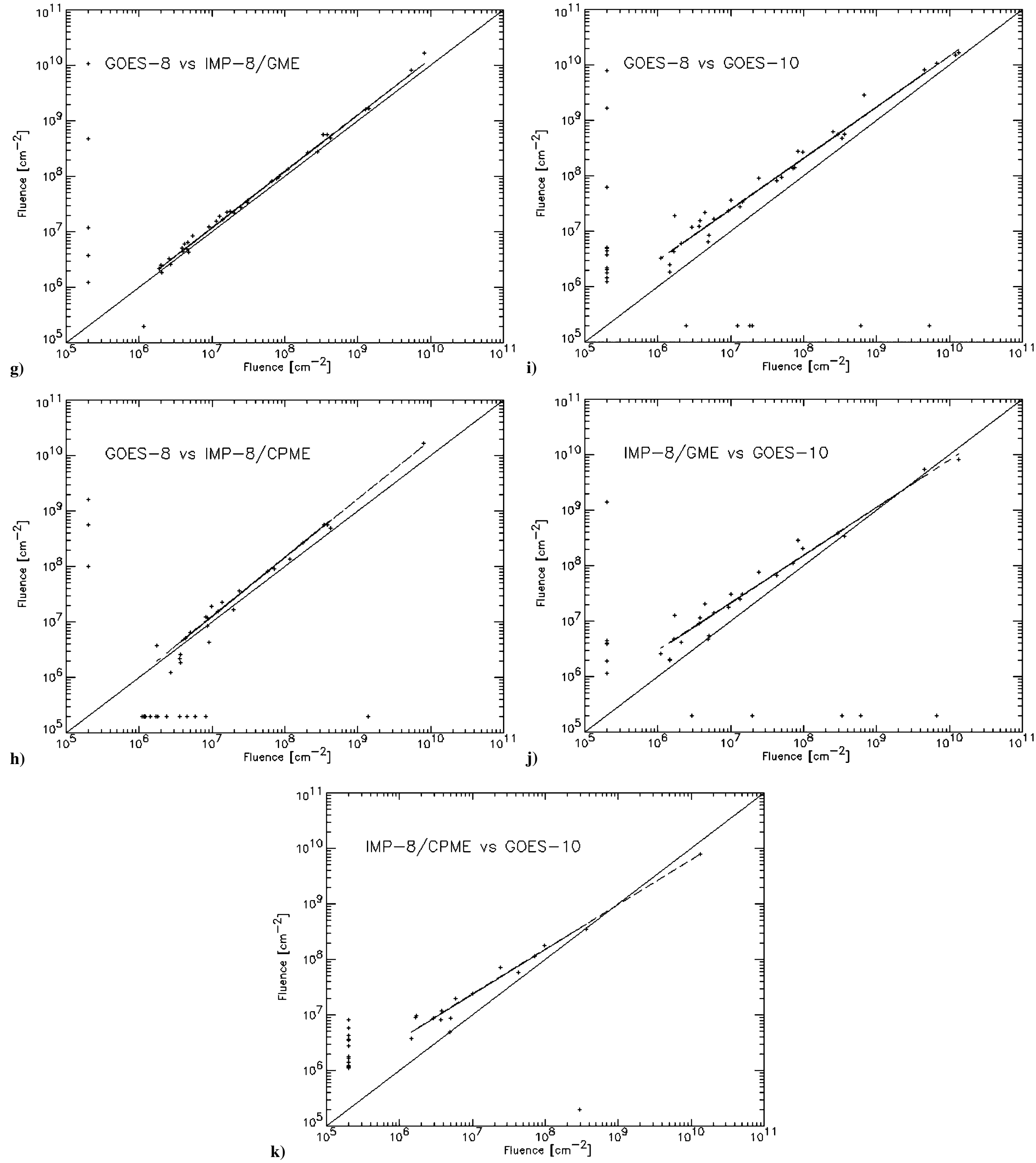

Fig. 7 Intercalibration of event fluences measured by different instruments operating simultaneously (continued).

Comparisons between IMP-8, GOES-7, and GOES-8 show that these instruments are in good agreement for most events except that the CPME monitor measures lower fluences during the largest events compared to the other instruments. The reason for this might be because of the problem just reported in the IMP-8/CPME detector during the peak time of the events.[14] Also, the discrepancies of the number of events detected by these latter four instruments are relatively lower, which also indicates a good agreement between these data sets.

To assess the effect that the use of different data sets have on model output and also to identify the differences in the data sets that cause this effect, event lists during the period when GOES-8 and IMP-8/GME operated simultaneously (1 March 1996–26 October 2001) have been studied in more detail. The parameter estimates, following the procedure just described, were derived for the two different events list. The corresponding quantiles for a one-year mission are shown in Fig. 8 as the solid line and the dotted line for GOES-8 and IMP-8/GME, respectively. The large departure between the two different models (almost a factor 3 of the 90th quantile), although derived during identical time periods and with reasonably well-calibrated instruments, suggests that additional differences in the two data sets must impact model output. To find these differences, the effect of the difference of the instruments calibration needs to be eliminated. This is done via the use of Table 3 to adjust the event fluences observed by IMP-8/GME to match the GOES-8 fluences and use this new cross-calibrated IMP-8/GME dataset as input to the model (dashed line in Fig. 8). Now the discrepancy between the 90th quantile values is reduced by almost 50%. Furthermore, an

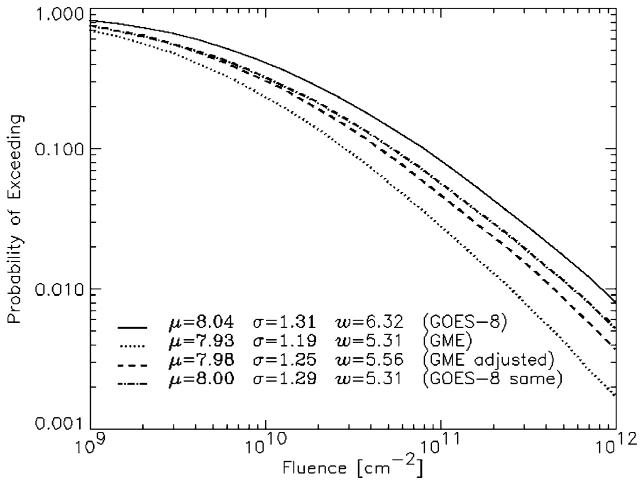

Fig. 8 Examples of fluence probability curves for protons with energy above 10 MeV for a one-year mission calculated with four different events list over the same period 1995–2001: GOES-8, IMP-8/GME, IMP-8/GME recalibrated match the GOES-8 fluences, and GOES-8 fluences without the events not detected by IMP-8/GME.

event-to-event examination of the two data sets revealed that some events identified by GOES-8 are missed in the IMP-8/GME data as a result of some large data gaps. The derived model quantiles based on the adjusted IMP-8/GME fluences and the GOES-8 fluences after suppressing from it the events missed in IMP-8/GME (dashed-dotted line in Fig. 8) shows now a very small discrepancy. The preceding analysis has shown how sensitive the model output is to small difference in calibration and discrepancy in event detection. A manual inspection of the data has shown that the discrepancy in event detection can be caused by several causes including data gap (event can be missed) or data errors (false event can be counted), and the separation of events into multiple events by one instrument but treated as one large event in another one.

VII. Toolkit for Updating Models

A. Quality Check Procedure

The preceding analysis has shown and quantified the impact of error in calibration, data gaps, and artificial events on the JPL approach to generate a solar proton statistical model. The analysis of Sec. VI shows that the IMP-8, GOES-7, and GOES-8 data sets are the ones closest to an ideal cross calibration. Because all data providers tend to produce the best possible calibration, this clustering of value for these three data sets suggests that they are the best basis as a reference data source for solar proton fluence measurements. A quality check of these data sets is necessary in order to extract ghost events and identify missed events caused by data gaps. To avoid manual inspection of each individual event, the different data sets in Table 1 were compared. Whenever an event was identified in one data set but not by the other during the same time period, closer examination of that event revealed if the instrument suffered from gaps or single data errors. This way possible artificial events have been removed, and missed events been accounted for in the final list. However, in the period when IMP-8 was operating there are few other data sources to compare with; hence, it is hard to account for missed events in IMP-8 (e.g, caused by data gaps) up to the start of the GOES satellites. As shown in Sec. VI and illustrated in Fig. 8, this can be the cause of nearly a factor 2 uncertainty in the model output for the 90th quantile.

The resulting list of solar proton events from 1 January 1974 to May 2002 is found in Table A1 in Appendix A. The table consists of six columns including the date of the start of the event given in month/day/year, the end of the event given in month/day/year, the duration of the event given in days, the total event fluence in cm^{-2} for protons greater than 10 MeV, and a reference to the source of the data (e.g., IMP-8/GME or GOES-7, 8). For more specific information on the data handling for the different data sources, we refer to Secs. II and III. To validate the accuracy of the results, the reference lists have also been compared to a number of existing databases of solar particle events, Feynman et al.[7] and Goswami et al.[15] for solar cycle 21, a list of preliminary event fluences from NOAA (H. H. Sauer, private communication) for solar cycle 22, and the set of major solar cycle 23 events from CDAW. All events identified are also found in the preceding databases with a few exceptions that might be caused by different event selection procedures. In general, the fluence values from Sauer corresponded very closely to the fluences detected by GOES-7. Events in Table A1 that were also identified by these existing databases have been marked by footnotes.

B. Possible Model Update and Tools

The new list of events covers the majority of the last three solar cycles and is used in the following to generate a possible update of the JPL model for protons with energy above 10 MeV. The division of the solar cycle into solar active and inactive years as proposed by Feynman et al.[7] has been verified by a superimposed epoch analysis of the annual fluence for the 36 years covered by this list. The time of solar maximum is derived from the 13-month running mean value of the international sunspot number (SIDC) with an accuracy of 0.1 years, and the year is defined as a 365-day periods centered on this time. Figure 9 shows the result of this analysis, and a clear difference of more than an order of magnitude between the four inactive years and the seven active years can be seen. Hence, the approach to consider the fluence during only the active years seems relevant for long-duration missions cumulated fluence estimate and has also been adopted in this study.

An example of a possible model prediction using the up-to-date list of events in Appendix A from year 1974 to year 2002 is shown in Fig. 10. The parameter values, derived by the method described in Sec. II, are $\mu = 8.07$ ($\log_{10}$), $\sigma = 1.10$ ($\log_{10}$), and $w = 6.15$ events per solar active year. It can be seen that the prediction of the updated model is typically larger than that from the JPL-91 model (e.g., the 90th quantile is about a factor 2 higher). A sensitivity analysis of the parameters estimates to the threshold value was again performed on this data set, and figures similar to those in Sec. IV were obtained.

If only data from IMP-8/CPME were used, the larger SEP events fluence would have been significantly lower than in the list of Appendix A, and as a result an updated model based on such an event list would have been much closer to the old JPL-91 model, as actually observed by Feynman et al.[10] According to the preceding analysis, the list in Appendix A is a better choice because of the various caveats known for the IMP/CPME data set, including the large data gaps and the saturation effects observed during high-intensity events, which are the most significant in such model predictions (compare analysis in Sec. VI).

C. Using Data Before 1974

Because the accuracy of the JPL approach to generate models is a priori limited by the amount of available SEP data as shown recently

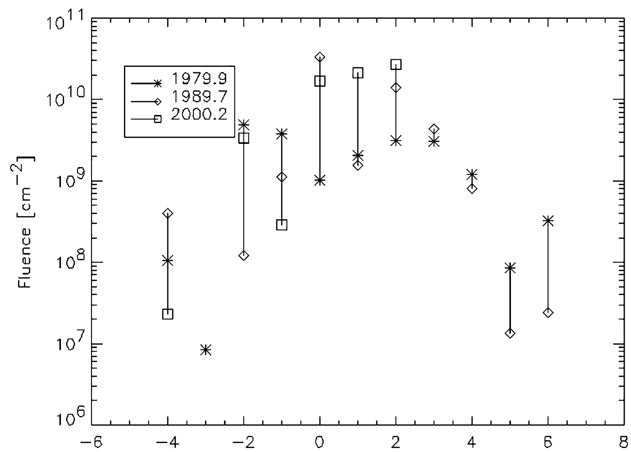

Fig. 9 Superimposed epoch analysis of yearly event fluences of protons with energy above 10 MeV in the period 1974–2002 (solar cycle 21, 22, and 23). The dates of solar maximum for each solar cycle are indicated in the box.

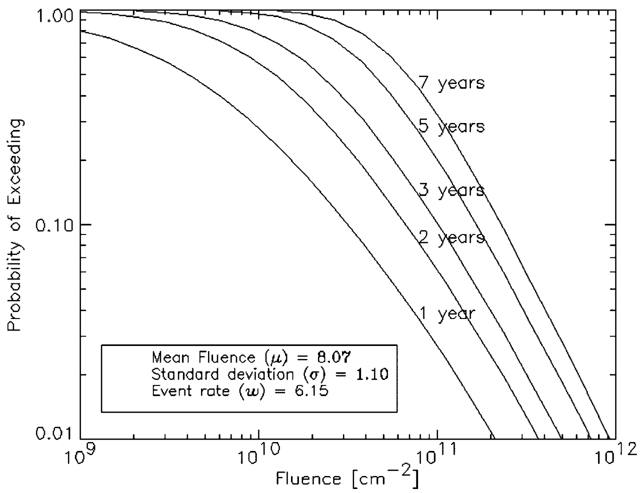

Fig. 10 Fluence probability curves for protons above 10 MeV for the model based on the reference list in Appendix A (1974–2002) and the derived model parameters shown in the box.

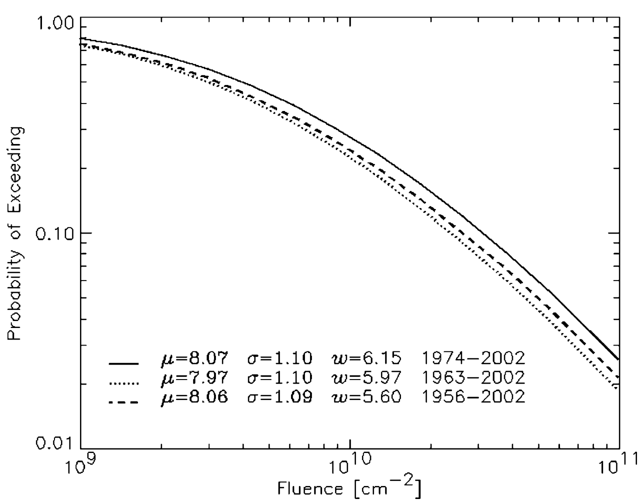

Fig. 11 Examples of fluence probability curves for protons above 10 MeV for a one-year mission based on the reference list in Appendix A (1974–2002), when adding the events from Feynman et al.[7] from 1963–1974, and when adding the events from Feynman et al.[7] from 1956–1974.

by Rosenqvist and Hilgers,[6] it might be appropriate to use also in the model the data from Feynman et al.[7] collected up to 1974 from space-based instruments and the data collected from 1956 to 1963 derived from balloons and ground-based instruments although the quality of these data is not known. The effect on the model output of adding the space data from 1963 to 1974 and the ground-based data from 1956 to 1963 is shown in Fig. 11. It can be seen that the overall impact of adding the data before 1974 is at most about 20% on the 90th quantile. Because this difference is less than the overall uncertainty of the model output when using the data from 1974 to 2002, including these data as input to the model is not necessary.

D. Using Data Beyond 2003

Since the termination of GOES-8 on 8 April 2003, currently the only data that can be used to further update statistical models are from the GOES-12 or the GOES-10 satellite. Because of the known and recently discovered caveats in both GOES-10 and GOES-12 (see Sec. III), another method is proposed for future updates. The approach is to use GOES-10 but to apply the cross-calibration relation found in Sec. VI to align the GOES-10 fluences to match the fluences observed in GOES-8. The adjustments are made by simply applying Eq. (5) to the GOES-10 fluences and use the values of l and d found in Table 3:

$$\log(F_{\text{GOES-10 corrected}}) = l + d \cdot \log(F_{\text{GOES-10}}) \tag{5}$$

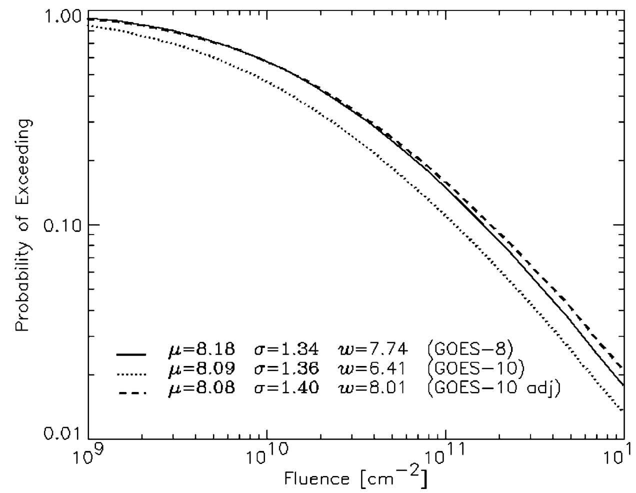

Fig. 12 Examples of fluence probability curves for proton above 10 MeV for a one-year mission calculated with the three different events list over the same period (1998–2002), GOES-8, GOES-10, and GOES-10 recalibrated to match the GOES-8 fluences.

To validate this approach, the quantiles for the three respective data sets, GOES-8, GOES-10, and GOES-10 corrected, during a time period when both spacecraft were operating (08/01/1998–06/17/2002) have been derived for a mission duration of one year. Figure 12 shows that the discrepancy between the models is very small after applying the correction to the GOES-10 fluences. Hence, using GOES-10 data corrected according to the relation found with GOES-8 appears as a reasonable approach for future updates.

VIII. Summary

In this paper, the stability of the quantiles derived from a SEP cumulated fluence model has been investigated with respect to the effect of the fitting procedure, the flux and fluence threshold, and the use of different data sources. The modeling approach is directly derived from the method elaborated by Feynman et al.[1,7] and differs only via the best-fit technique of the event fluences by a $\log_{10}$-normal law. The approach is implemented as a fully reproducible computer-based procedure; therefore, it can easily be applied to any new data set. The prediction of the yearly cumulated fluence probability curves based on the fitting approach used in this paper has been shown to be more stable when applied to different SEP sample data sets than the method previously used for JPL-91 and JPL-85, as can be seen in Fig. 5. Furthermore, a test of the sensitivity of the method to fluence threshold value for the selection of events has shown no significant effect over the range investigated, confirming that a threshold of 10^7 cm^{-2} is reasonable.

Differences in the model output when examining a range of different data sources were found to be mainly caused by four critical issues, the cross calibration of the sources, data errors and missed events, and the division of events into multiple or single events. An example was shown when the 90th quantiles could differ by about a factor two even though it was derived from data observed during identical time periods but from different sources. This discrepancy vanishes when correcting for the preceding issues. This investigation has shown that, with the current knowledge on data quality, the available data sets that minimize the effect of the identified sources of uncertainty on model output and covers the period of interest are the GOES-7, GOES-8, and IMP-8/GME data sets.

Finally, a list of events has been generated based on the selection criteria from Feynman et al.[1,7] and on the data sets that were found to provide the most reliable data. Careful inspection of the events has been performed in order to extract ghost events caused by data errors or to account for missing events in one instrument. However, in the period covered by IMP-8, there are few other data sources with which to compare; hence, it is hard to account for missed events up to the start of the GOES satellites. This list of events can be used to generate a set of coefficients as input of a SEP cumulated fluence of the type of Feynman et al.[7]

The philosophy that we promote by providing this material is that the space engineering community should standardize methods of creating and applying statistical models and approve reference data sets. Model details should be open so that methods and results can be reproduced. We hope that the current paper, which can be seen as a continuation of the pioneering work from Feynman et al.[1,7] and which includes all details for reproducing the parameter estimate and the model generation, will contribute to raise interest for such an approach.

Furthermore, the method of error analysis, the data quality check procedure, and the list of events attached in the Appendices are general enough to be applicable to check other models like the ones from King,[4] Nymmik,[3] or Xapsos et al.[5] The later model of cumulative fluence from Xapsos et al.[5] should be less sensitive to data errors and to the structure of the events because it is based on yearly averaged fluence. A thorough analysis of this model is beyond the scope of the present paper but should be foreseen in the near future.

Appendix A: Solar Proton Events

Table A1 Solar proton events from 1 January 1974 to May 2002

Index	Start date (mm/dd/yy)	Stop date (mm/dd/yy)	Duration, days	Fluence >10 MeV, cm^{-2}	Reference
1	06/09/74	06/10/74	1	1.69e+06	IMP8/GME[a]
2	07/03/74	07/09/74	6	3.56e+08	IMP8/GME[a,b]
3	09/11/74	09/17/74	6	2.67e+08	IMP8/GME[a,b]
4	09/20/74	09/28/74	8	1.38e+08	IMP8/GME[a,b,c]
5	11/05/74	11/07/74	2	1.36e+07	IMP8/GME[a]
6	08/21/75	08/23/75	2	5.02e+06	IMP8/GME[a]
7	04/30/76	05/03/76	3	1.01e+08	IMP8/GME[a,b]
8	08/22/76	08/24/76	2	8.45e+06	IMP8/GME[a]
9	09/09/77	09/15/77	6	1.54e+07	IMP8/GME[a]
10	09/17/77	09/22/77	5	3.50e+08	IMP8/GME[a,b,c]
11	09/24/77	09/28/77	4	8.82e+07	IMP8/GME[a,b]
12	10/12/77	10/13/77	1	2.33e+06	IMP8/GME[a]
13	11/22/77	11/26/77	4	3.00e+08	IMP8/GME[a,b]
14	01/02/78	01/05/78	3	5.43e+06	IMP8/GME[a]
15	02/13/78	02/18/78	5	1.74e+09	IMP8/GME[a,b]
16	04/08/78	04/09/78	1	1.09e+06	IMP8/GME[a]
17	04/11/78	04/14/78	3	4.81e+07	IMP8/GME[a,b,c]
18	04/17/78	05/10/78	23	2.35e+09	IMP8/GME[a,b,d]
19	05/31/78	06/03/78	3	1.44e+07	IMP8/GME[a,b]
20	06/23/78	06/26/78	3	5.17e+07	IMP8/GME[a]
21	07/12/78	07/16/78	4	2.08e+07	IMP8/GME[a,b]
22	09/08/78	09/09/78	1	1.54e+06	IMP8/GME[a]
23	09/23/78	09/29/78	6	3.32e+09	IMP8/GME[a,b]
24	10/09/78	10/11/78	2	7.82e+06	IMP8/GME[a]
25	11/10/78	11/13/78	3	1.79e+07	IMP8/GME[a,b]
26	12/12/78	12/14/78	2	2.58e+06	IMP8/GME[a]
27	02/17/79	02/20/79	3	1.20e+07	IMP8/GME[a]
28	03/03/79	03/06/79	3	8.56e+06	IMP8/GME[a]
29	04/03/79	04/06/79	3	2.04e+07	IMP8/GME[a,b]
30	06/06/79	06/10/79	4	2.96e+08	IMP8/GME[a,b]
31	07/06/79	07/09/79	3	1.83e+07	IMP8/GME[a,b]
32	08/07/79	08/08/79	1	1.18e+06	IMP8/GME[a]
33	08/19/79	08/30/79	11	6.40e+08	IMP8/GME[a,b]
34	09/09/79	09/13/79	4	5.26e+06	IMP8/GME[a]
35	09/15/79	09/29/79	14	3.11e+08	IMP8/GME[a,b,c]
36	11/16/79	11/18/79	2	4.16e+07	IMP8/GME[a,b]
37	01/11/80	01/12/80	1	1.22e+06	IMP8/GME[a]
38	02/07/80	02/08/80	1	1.31e+06	IMP8/GME[a]
39	04/04/80	04/06/80	2	5.36e+06	IMP8/GME[a]
40	07/18/80	07/26/80	8	1.48e+08	IMP8/GME[a,b]
41	08/07/80	08/08/80	1	1.62e+06	IMP8/GME
42	10/15/80	10/21/80	6	2.95e+07	IMP8/GME[a,b]
43	11/15/80	11/18/80	3	4.37e+06	IMP8/GME[a]
44	11/24/80	11/25/80	1	4.87e+06	IMP8/GME[a]
45	11/30/80	12/01/80	1	1.83e+06	IMP8/GME[a,c]
46	03/30/81	04/06/81	7	7.56e+08	IMP8/GME[a,b]
47	04/10/81	04/13/81	3	6.42e+07	IMP8/GME[a,b]
48	04/15/81	04/19/81	4	1.17e+07	IMP8/GME[a,b,c]
49	04/24/81	05/21/81	27	1.06e+09	IMP8/GME[a,b,d]
50	07/20/81	07/26/81	6	8.41e+07	IMP8/GME[a,b]
51	08/09/81	08/11/81	2	9.57e+06	IMP8/GME[a,b]
52	09/07/81	09/09/81	2	7.03e+06	IMP8/GME[a]
53	09/19/81	09/25/81	6	1.18e+07	IMP8/GME[a,b]
54	10/08/81	10/21/81	13	1.85e+09	IMP8/GME[a,b]
55	11/11/81	11/12/81	1	1.57e+06	IMP8/GME[a]
56	12/06/81	12/08/81	2	4.73e+06	IMP8/GME[a]
57	12/10/81	12/12/81	2	6.95e+07	IMP8/GME[a,b,c]

(Continued)

Table A1 Solar proton events from 1 January 1974 to May 2002 (continued)

Index	Start date (mm/dd/yy)	Stop date (mm/dd/yy)	Duration, days	Fluence >10 MeV, cm^{-2}	Reference
58	12/28/81	12/30/81	2	5.12e+06	IMP8/GME[a]
59	01/31/82	02/09/82	9	1.03e+09	IMP8/GME[a,b]
60	03/07/82	03/09/82	2	8.92e+06	IMP8/GME[a,b]
61	06/07/82	06/17/82	10	5.21e+07	IMP8/GME[a]
62	06/28/82	06/29/82	1	2.42e+06	IMP8/GME
63	07/11/82	07/20/82	9	1.52e+09	IMP8/GME[a,b]
64	07/22/82	07/26/82	4	1.15e+08	IMP8/GME[a,b]
65	09/05/82	09/07/82	2	1.45e+07	IMP8/GME[a,b]
66	11/22/82	12/22/82	30	1.08e+09	IMP8/GME[a,b,d]
67	12/26/82	12/31/82	5	2.39e+08	IMP8/GME[a,b]
68	02/03/83	02/06/83	3	8.29e+07	IMP8/GME[a,b]
69	06/15/83	06/18/83	3	1.45e+07	IMP8/GME[a,b]
70	02/01/84	02/02/84	1	1.24e+06	IMP8/GME[a]
71	02/16/84	02/24/84	8	1.43e+08	IMP8/GME[a,b,d]
72	03/13/84	03/17/84	4	2.82e+07	IMP8/GME[a,b]
73	04/25/84	05/07/84	12	1.03e+09	IMP8/GME[a,b,d]
74	05/24/84	05/25/84	1	2.72e+06	IMP8/GME
75	01/22/85	01/24/85	2	5.86e+06	IMP8/GME[a]
76	04/24/85	04/28/85	4	7.95e+07	IMP8/GME[a,b]
77	07/09/85	07/10/85	1	1.53e+07	IMP8/GME[a,b]
78	02/05/86	02/12/86	7	1.29e+08	IMP8/GME[b]
79	02/14/86	02/19/86	5	1.76e+08	IMP8/GME[b]
80	03/06/86	03/08/86	2	3.97e+06	IMP8/GME
81	11/08/87	11/10/87	2	2.81e+07	GOES7[e]
82	12/30/87	01/01/88	2	5.46e+06	GOES7
83	01/03/88	01/07/88	4	8.78e+07	GOES7
84	03/26/88	03/27/88	1	2.80e+06	GOES7
85	06/30/88	07/01/88	1	3.27e+06	GOES7
86	08/25/88	08/31/88	6	1.41e+07	GOES7
87	10/05/88	10/06/88	1	1.18e+06	GOES7
88	10/12/88	10/13/88	1	2.13e+06	GOES7
89	11/08/88	11/11/88	3	7.18e+06	GOES7
90	11/14/88	11/15/88	1	1.98e+06	GOES7
91	12/15/88	12/20/88	5	1.88e+07	GOES7
92	01/05/89	01/06/89	1	2.40e+06	GOES7
93	03/08/89	03/21/89	13	1.05e+09	GOES7[e]
94	03/23/89	03/25/89	2	1.00e+07	GOES7
95	04/11/89	04/17/89	6	2.01e+08	GOES7[e]
96	04/23/89	04/24/89	1	2.62e+06	GOES7
97	05/01/89	05/09/89	8	4.05e+07	GOES7[e]
98	05/22/89	05/29/89	7	2.20e+07	GOES7
99	06/18/89	06/20/89	2	3.58e+06	GOES7
100	06/30/89	07/02/89	2	4.21e+06	GOES7
101	07/25/89	07/27/89	2	1.59e+07	GOES7
102	08/12/89	09/06/89	25	7.84e+09	GOES7[e]
103	09/12/89	09/17/89	5	2.81e+07	GOES7
104	09/29/89	10/13/89	14	3.86e+09	GOES7[e]
105	10/19/89	11/10/89	22	1.91e+10	GOES7[e]
106	11/15/89	11/17/89	2	1.25e+07	GOES7
107	11/27/89	12/05/89	8	2.20e+09	GOES7[e]
108	03/19/90	03/22/90	3	7.24e+08	GOES7[e]
109	03/29/90	03/30/90	1	3.31e+06	GOES7
110	04/07/90	04/10/90	3	2.00e+07	GOES7
111	04/12/90	04/13/90	1	1.21e+06	GOES7
112	04/16/90	04/23/90	7	3.29e+07	GOES7
113	04/28/90	04/30/90	2	7.23e+07	GOES7[e]
114	05/08/90	05/10/90	2	2.74e+06	GOES7
115	05/16/90	06/01/90	16	3.60e+08	GOES7[e]
116	06/12/90	06/14/90	2	3.60e+07	GOES7
117	07/26/90	08/06/90	11	1.98e+08	GOES7[e]
118	08/13/90	08/15/90	2	3.56e+06	GOES7
119	01/28/91	02/02/91	5	8.70e+07	GOES7[e]
120	02/08/91	02/10/91	2	4.55e+06	GOES7
121	02/25/91	02/27/91	2	4.47e+06	GOES7
122	03/13/91	03/16/91	3	1.21e+07	GOES7
123	03/23/91	04/09/91	17	9.11e+09	GOES7[e]
124	04/23/91	04/24/91	1	2.52e+06	GOES7
125	05/10/91	05/15/91	5	1.37e+08	GOES7[e]
126	05/19/91	05/28/91	9	2.47e+07	GOES7
127	05/31/91	06/21/91	21	3.20e+09	GOES7[e]
128	06/30/91	07/13/91	13	1.16e+09	GOES7[e]
129	08/26/91	08/31/91	5	1.25e+08	GOES7[e]
130	09/07/91	09/08/91	1	1.30e+06	GOES7

(Continued)

Table A1 Solar proton events from 1 January 1974 to May 2002 (continued)

Index	Start date (mm/dd/yy)	Stop date (mm/dd/yy)	Duration, days	Fluence >10 MeV, cm^{-2}	Reference
131	09/30/91	10/03/91	3	1.33e+07	GOES7
132	10/28/91	11/01/91	4	2.94e+07	GOES7
133	12/29/91	12/30/91	1	1.09e+06	GOES7
134	02/07/92	02/09/92	2	4.72e+07	GOES7
135	02/27/92	02/28/92	1	1.90e+06	GOES7
136	03/08/92	03/09/92	1	2.62e+06	GOES7
137	03/15/92	03/18/92	3	8.83e+06	GOES7
138	05/09/92	05/14/92	5	5.84e+08	GOES7[e]
139	05/24/92	05/25/92	1	1.13e+06	GOES7
140	06/25/92	07/02/92	7	2.85e+08	GOES7[e]
141	08/06/92	08/08/92	2	6.99e+06	GOES7
142	10/30/92	11/08/92	9	3.47e+09	GOES7[e]
143	11/29/92	11/30/92	1	2.10e+06	GOES7
144	03/04/93	03/09/93	5	1.46e+07	GOES7
145	03/12/93	03/15/93	3	2.17e+07	GOES7
146	06/07/93	06/08/93	1	1.49e+06	GOES7
147	02/20/94	02/23/94	3	8.01e+08	GOES7[e]
148	10/20/94	10/21/94	1	1.34e+07	GOES7
149	08/12/95	08/13/95	1	1.32e+06	GOES7
150	10/20/95	10/22/95	2	2.29e+07	GOES8
151	11/04/97	11/11/97	7	4.89e+08	GOES8[d,f]
152	04/20/98	04/27/98	7	1.62e+09	GOES8[f]
153	04/30/98	05/11/98	11	1.00e+08	GOES8[d,f]
154	06/17/98	06/19/98	2	2.55e+06	GOES8
155	08/23/98	09/01/98	9	5.69e+08	GOES8
156	09/24/98	09/26/98	2	4.30e+06	GOES8
157	09/30/98	10/04/98	4	5.60e+08	GOES8
158	10/19/98	10/20/98	1	1.85e+06	GOES8
159	11/06/98	11/09/98	3	8.39e+06	GOES8
160	11/14/98	11/18/98	4	1.37e+08	GOES8
161	01/21/99	01/25/99	4	1.67e+07	GOES8
162	04/24/99	04/27/99	3	1.90e+07	GOES8[f]
163	05/05/99	05/08/99	3	1.24e+07	GOES8[f]
164	05/27/99	05/28/99	1	2.15e+06	GOES8
165	06/02/99	06/08/99	6	9.06e+07	GOES8[d,f]
166	02/18/00	02/20/00	2	5.10e+06	GOES8[f]
167	04/04/00	04/07/00	3	3.61e+07	GOES8[f]
168	06/07/00	06/13/00	6	8.27e+07	GOES8[d,f]
169	06/26/00	06/27/00	1	1.21e+06	GOES8
170	07/13/00	07/24/00	11	1.65e+10	GOES8[d,f]
171	07/28/00	07/30/00	2	6.37e+06	GOES8[f]
172	09/12/00	09/18/00	6	2.66e+08	GOES8[f]
173	10/16/00	10/19/00	3	1.56e+07	GOES8[f]
174	10/25/00	10/28/00	3	1.20e+07	GOES8[f]
175	10/31/00	11/02/00	2	3.74e+06	GOES8
176	11/09/00	11/20/00	11	1.08e+10	GOES8
177	11/24/00	12/04/00	10	4.75e+08	GOES8[d,f]
178	01/22/01	01/24/01	2	3.26e+06	GOES8
179	01/28/01	01/31/01	3	3.34e+07	GOES8[f]
180	03/27/01	04/22/01	26	1.65e+09	GOES8[d,f]
181	04/27/01	04/29/01	2	4.47e+06	GOES8[f]
182	05/07/01	05/10/01	3	2.34e+07	GOES8[f]
183	05/20/01	05/22/01	2	4.99e+06	GOES8
184	06/15/01	06/18/01	3	2.18e+07	GOES8[f]
185	08/10/01	08/11/01	1	6.05e+06	GOES8[f]
186	08/16/01	08/26/01	10	2.77e+08	GOES8[f]
187	09/15/01	09/16/01	1	2.52e+06	GOES8[f]
188	09/24/01	10/12/01	18	8.21e+09	GOES8[d,f]
189	10/19/01	10/26/01	7	2.73e+07	GOES8[d,f]
190	11/04/01	11/13/01	9	1.50e+10	GOES8[f]
191	11/18/01	12/01/01	13	7.89e+09	GOES8[d,f]
192	12/26/01	01/08/02	13	6.29e+08	GOES8[f]
193	01/10/02	01/19/02	9	1.42e+08	GOES8
194	01/27/02	01/28/02	1	2.07e+06	GOES8
195	02/20/02	02/21/02	1	1.76e+06	GOES8
196	03/16/02	03/24/02	8	6.23e+07	GOES8
197	04/17/02	04/29/02	12	2.85e+09	GOES8
198	05/01/02	05/02/02	1	1.45e+09	GOES8
199	05/22/02	05/25/02	3	9.29e+07	GOES8

[a]Also identified by Feynman et al.[7] [b]Also identified by Goswami et al.[15] [c]Included in the preceding event in the reference. [d]Divided into several events in the reference. [e]Also identified by Sauer (private communication, 1995). [f]Also identified by CDAW.

Appendix B: Model Algorithm

```
;ESTEC/ESA TOS-EMA
;CREATOR:   Nov. 1999 A. Hilgers
;MODIFIED:  Jul. 2001 E. Sasot Samplon
;MODIFIED:  Mar. 2003 L. Rosenqvist
;The input to this program is:
;ww           Number of events per year
;mu           Average value of the log-10 of the intensity of the events
;sig          Variance of the log-10 of events
;xx           Scalar or vector of fluence values not to be exceeded
;tau          Mission duration in years
;gammaln,xx is a function used in the Compound_poisson function. It returns the value ;of
ln(Gamma(xx) for xx>0.
;SOURCE: Numerical Recipies in Fortran [7]

function Compound_poisson,ww,mu,sig,tau,xx

nmax=150        ;Max number of events over the period considered. For
                ;tau larger than 7 years this may have to be increased to
                ;enhance accuracy.
npre=100000     ;Number of random sets to derive the probability of the sum
                ;of n<nmax log-normal distribution by Monte-Carlo simulation.
                ;May have to be increased for very rare fluence range.

crit=1.d-10     ;criteria of accuracy

nmin=30         ;A minimum number of iterations is needed in the loop on the
                ;sum of the events because the test variable behaviour with ii ;is not monotone
                [E. Sasot Samplon, private communication, 2001].

;Find out if xx is a scalar (with size) and if it is set it to a double
;value variable
sx=size(xx)
if sx(0) eq 0 then xx=[double(xx)]

nx=n_elements(xx)
crit=crit/float(nx)

;array to store the probability to exceed each fluence value in xx in
probt=dblarr(nx)

bbb=0.d0
test=1.d0 & ii=0

;Loop until the criteria and maximum or minimum iterations are fulfilled
while((ii le nmax-1) and ((test gt crit) or (ii le nmin))) do begin
       ;log10-normally distributed fluence values
       bbb=bbb+exp((randomn(seed,npre)*sig+mu)*alog(10.))
       test=0.d0
       ;(Monte-Carlo) loop over all fluence values in xx
        for jj=0,nx-1 do begin
              x=xx(jj)
              ;Find how many dimensions bbb above the fluence value in x have     ;and the
              size of ;each dimension
             uuu=size(where(bbb lt x))
             ;Probability that the sum of all fluences due to n events will ;exceed 10^F

             ;MODIFICATION: Changed uuu from uuu=size(where(bbb lt x) to correct
             ;instability problem when ww is low (L. Rosenqvist)
             uuu=size(where(x le bbb))
             ;Find how many dimension
             proba=uuu(0)*uuu(1)/(npre+1.d0)
             ;Proba times the probability of n event occurring during a mission of ;length
             tau if an average of ww events occurred per year during the ;observation period
             (Poisson prob)
             proba=proba*exp(-ww*tau+(ii+1)*alog(ww*tau) -gammaln(ii+2))
             ;Accumulate the probability over the while loop
             probt(jj)=proba+probt(jj)
             test=test+proba
      endfor
      ii=ii+1
endwhile
if (sx(0) eq 0) then return, probt(0) else return, probt
end
```

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