Re-calculating NOAA GOES integral solar proton fluxes

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The GOES integral solar proton fluxes constitute one of the most heavily used space weather products. They involve estimate of the fluxes above 1, 5, 10, 30, 50, 60 and 100 MeV. Unlike the GOES integral electron fluxes (e.g., >2 MeV), the integral solar proton fluxes are not directly measured; rather, they are derived from the differential number fluxes reported from the GOES Energetic Particle Sensor (EPS) channels. While this would seem to be a straightforward procedure, the broad EPS energy-dependent geometrical factors make the effective energies of these differential fluxes inherently ambiguous. Additional information on the energy spectra being measured is needed to resolve this ambiguity. The builder of the EPS [Panametrics, 1995] as well as the developers of the NOAA integral flux algorithms [Zwickl, 1989; Rodriguez et al., 2009] recognized that the effective energy depends on the proton energy spectrum. A recent exhaustive cross-calibration of the GOES EPS with the higher resolution IMP-8 Goddard Medium Energy (GME) experiment shows that this effective energy lies within a relatively narrow energy range. Therefore, within the observed variability of solar proton spectra, E_{eff} can be treated as a constant [Sandberg et al., 2014]. In the present study, we compare integral fluxes calculated using the NOAA algorithms with those calculated using the cross-calibrated effective energies of Sandberg et al. [2014]. This comparison reveals significant discrepancies that increase with increasing energy. After summarizing the potential implications for the integral flux products, we identify several lines of inquiry for resolving the discrepancies.

NOAA Integral Flux Algorithms

Since 1989, NOAA has calculated integral fluxes using an algorithm developed for GOES-7 [Zwickl, 1989]. First, the channel fluxes are averaged over 5 minutes and corrected for contamination by higher energy protons; the backgrounds (due to GCRs in the higher energy channels) are also removed. This product is archived and made available to the public along with the integral fluxes, and we use it as the starting point for all the integral flux calculations shown in this poster. A piecewise power law spectrum of differential flux is calculated from a linear regression on the natural logarithm of counts ratios in adjacent channels using fixed empirical parameters, and this spectrum is integrated to derive integral flux. This (GOES-7) algorithm has been used to produce integral fluxes from GOES-7 through -15.

With the new solar proton instrument on GOES-R (scheduled for launch in 2016), a new Integral Flux algorithm was needed. In order to demonstrate data continuity, an algorithm was developed that could operate on both the old and new instrument channel fluxes. At its heart is a procedure by which the piecewise power law (represented by the exponent γ) and the effective channel energies (E_i) could be calculated iteratively. This procedure uses the following expression, which treats the channel responses as a boxcar in energy [Rodriguez et al., 2009; Kress et al., 2013]:

$$E_i = \left[\frac{(-\gamma+1)\,(E_u - E_l)}{\left(E_u^{-\gamma+1} - E_l^{-\gamma+1}\right)} \right]^{\frac{1}{\gamma}},$$

Cross-calibration of GOES EPS and IMP-8 GME

In a recent work, Sandberg et al. [2014], performed a cross-calibration analysis for several GOES EPS units using high resolution corrected measurements of IMP-8 GME dataset. The analysis was based on a succesive comparison of GOES measurements with GME measurements re-binned at an ultra dense energy grid without making any a priori use of the detection characteristics of GOES/EPS channels. This study showed that their effective energy lies within a relatively narrow energy range compared to the nominal detection energy range of the high energy channels. In addition, the effective energy values for the P2-P7 channels were determined in order to provide the best agreement with the calibration characteristics of the IMP8/GME scientific instrument.

Channel Name	EPS-2 E_{nom} (MeV)	GOES-8 E_{eff} (MeV)	GOES-11 E_{eff} (MeV)
P2	6.0 (4.0–9.0)	6.05 (4.0–7.9)	6.4 (5.0–7.9)
P3	11.6 (9.0–15.0)	10.6 (7.4–15.0)	12.5 (9.4–15.9)
P4	24.5 (15–40.0)	19.0 (13.3–21.3)	20.8 (16.7–23.2)
P5	56.6 (40–80)	47.8 (37.0–53.6)	46.1 (32.5–56.4)
P6	115 (80–165)	107. (91.5–113)	104. (89.8–114)
P7	287 (165–500)	153. (119–179)	148. (120–186)

Table 1: Nominal and effective energy values for the P2-P7 channels of GOES08/EPS and GOES11/EPS.

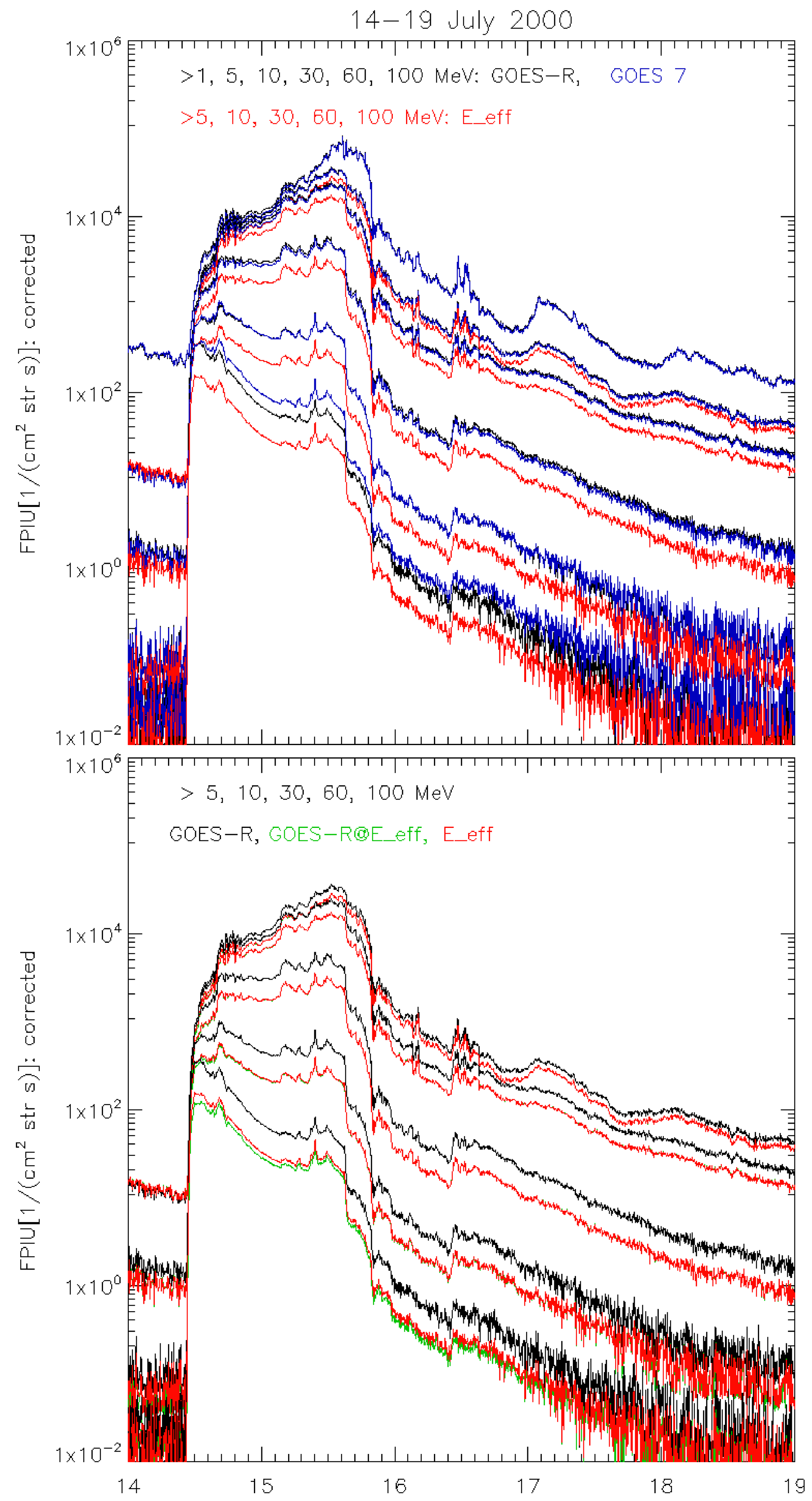

Figure 1: Integral GOES08/EPS proton flux series for the 14-19 July 2000 solar proton event.

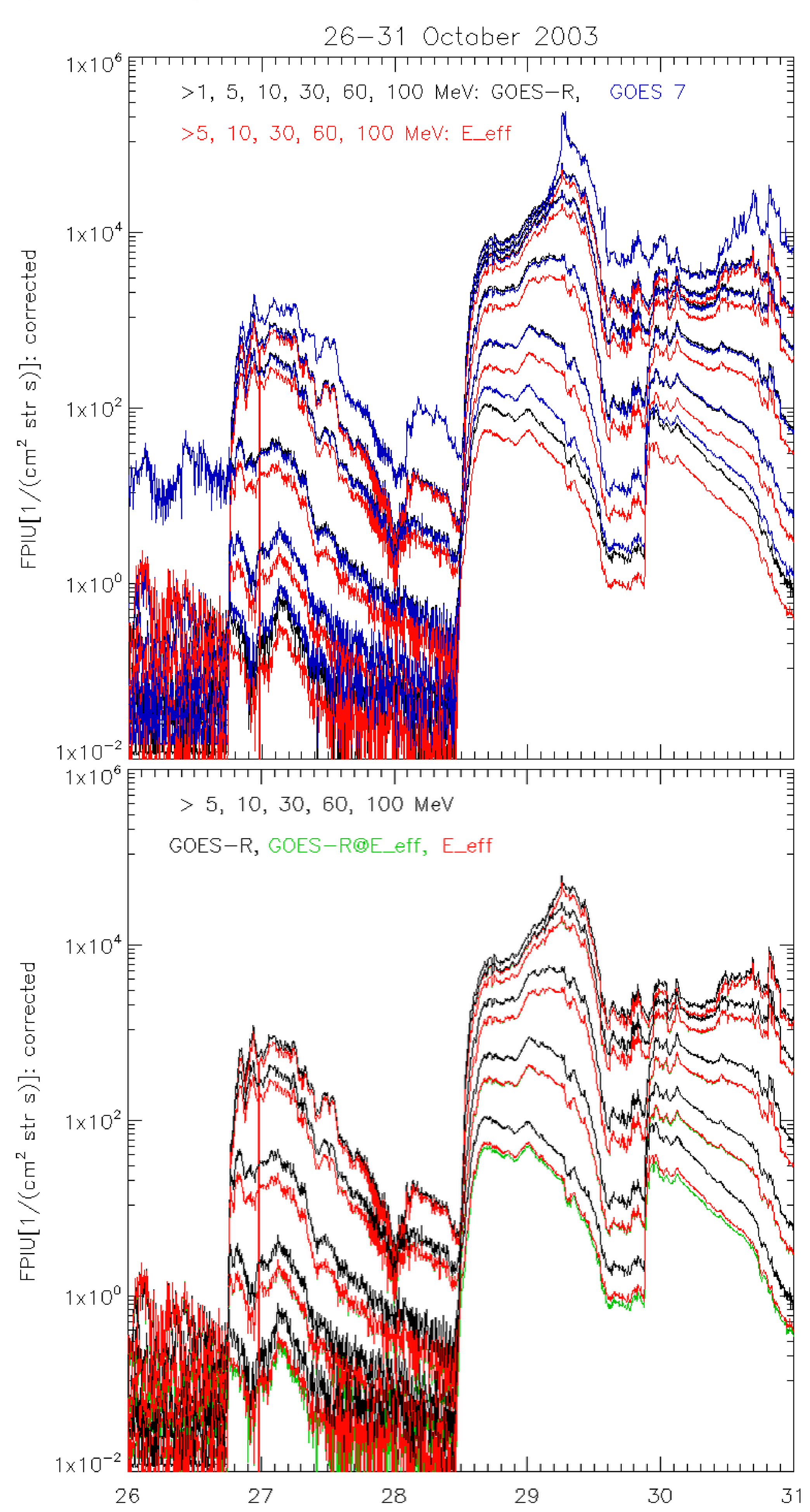

Figure 2: Integral GOES11/EPS proton flux series for the 26-31 October 2003 solar proton event.

Comparisons of Integral Flux Calculations

A large number of solar proton events have been selected and used for the derivation and comparison of GOES/EPS integral solar proton fluxes. In what follows, we present results for the July 2000 (Figure 1) and the October 2003 (Figure 2) events using measurements from the EPS units on-board GOES08 and GOES11.

Excellent agreement was achieved between the old (GOES-7) and the new (GOES-R) algorithms, except at the lowest (> 1 MeV) and highest (> 100 MeV) energies (upper panels at Figures 1-2). At the lowest energy, this was due to the mix of trapped and solar protons, with the trapped proton spectrum being ill constrained by the available data. At the highest energy, the discrepancy was due to the sensitivity to the choice of effective energy for the very broad P7 channel. The GOES-R >100 MeV fluxes were systematically smaller than the GOES-7 > 100 MeV fluxes by about a factor of 2.

Using the effective energies presented in Table 1, we calculate the integral fluxes using two algorithms. The results of these calculations are shown in Figures 1-2 (lower panels) for the selected SEP events at >5, 10, 30, 60 and 100 MeV. First, we used the GOES-R algorithm, but replacing the iterative E_i determination with use of the fixed E_{eff} (GOES-R@E_{eff} in Figs. 1-2). Second, by re-binning with a piece-wise power-low the EPS measurements in a dense grid of 100 energy values within an energy range of 5-330 MeV and performing a numerical integration in the resulted flux spectra (E_{eff} in Figs. 1-2). Apart from the >100 MeV fluxes, the agreement is excellent between the pair of integration methods when using fixed E_{eff}.

Large differences, however, exist between the fixed (E_{eff}) and the iterative GOES-R (and GOES-7) algorithms (upper panels at Figures 1-2). The differences between these pairs is substantial, about a factor of 2 at >30, and 60 MeV, less at >10 MeV. At >100 MeV, the difference between the largest (GOES-7) and the smallest (GOES-R@E_{eff}) is about a factor of 3. These differences are due to the consideration of different E_{eff} values. The relatively smaller values of E_{eff} (see Table 1) result in the derivation of smaller integral fluxes compared to those provided by GOES-7 and GOES-R codes.

Discussion and Paths Forward

The importance of this data product makes it imperative that we understand the source of these large discrepancies. At this time, it is not clear which approach is more accurate. At least two possibilities present themselves:

- Both GME and EPS were calibrated in proton beams. Perhaps their absolute calibrations were seriously inconsistent. Analysis indicates that they would have to be off by factors of 2-6 depending on the channel in order to explain the differences in E_{eff}. This magnitude of error seems unlikely.
- The treatment of the EPS channel responses as boxcar functions results in E_{eff} biased high. This is consistent with the tendency toward high energy tails in the energy-dependent geometrical factors..

In order to resolve these discrepancies, we will pursue the following lines of inquiry:

- Fold the differential proton flux GOES/EPS data with the full energy-dependent geometrical factors of EPS, using E_{iter} and E_{eff}, and compare the resulted count-rates with the observed ones.
- Calculate the EPS effective energies from a bowtie analysis of the EPS geometrical factors and compare them to the Sandberg et al. [2014] E_{eff}.
- Apply spectral retrieval techniques using full energy-dependent geometrical factors..

References

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