# AE9/AP9/SPM Radiation Environment Model

## Summary of AP9 V1.20 Monte Carlo issue and its fix in AP9 V1.30

The AE9/AP9/SPM model was developed by the Air Force Research Laboratory in partnership with MIT Lincoln Laboratory, Aerospace Corporation, Atmospheric and Environmental Research, Incorporated, Los Alamos National Laboratory and Boston College Institute for Scientific Research.

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The AE9/AP9/SPM model and related information can be obtained from AFRL's Virtual Distributed Laboratory (VDL) website: https://www.vdl.afrl.af.mil/programs/ae9ap9

V1.00.002 release: 05 September 2012

V1.03.001 release: 26 September 2012

V1.04.001 release: 20 March 2013

V1.04.002 release: 20 June 2013

V1.05.001 release: 06 September 2013

V1.20.001 release: 31 July 2014

V1.20.002 release: 13 March 2015

V1.20.003 release: 15 April 2015

V1.20.004 release: 28 September 2015

V1.30.001 release: 25 January 2016

In a future release of AE9/AP9/SPM, the model will be renamed to be "International Radiation Environment Near Earth" (IRENE).



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**Introduction**

In June 2015 we identified an issue in AP9 V1.20 which led to incorrect Monte Carlo results for very long mission runs (>3-4 years). The problem produced unrealistic increases in the amplitude of Monte Carlo dynamics after 2-4 years of simulation, especially for protons of low energy (<1-10 MeV) and high energy (>100-200 MeV). This resulted in (1) progressively increasing amplitudes of Monte Carlo variations during long runs and (2) unrealistic increases in Monte Carlo quantities (e.g. means, medians and percentiles) after multi-year mission periods.

Investigation showed that all versions of AP9 V1.20 suffered from a numerical instability in the matrices that evolved the Monte Carlo dynamics. The original stability test gave a false pass due to numerical noise in a critical matrix calculation (eigenvalue estimation). There was no issue for mean or perturbed mean runs of AP9, AE9, or SPM. The issue has not been detected in AE9 V1.20 Monte Carlo results.

We have instituted a more robust stability test that has allowed us to apply additional tapering of long lag correlations, as needed, to obtain a stable Monte Carlo simulation. These changes are applied in AP9 and AE9 V1.30 in development of the matrices governing Monte Carlo time evolution and with slight changes to the runtime code. In addition, we improved the Monte Carlo algorithms to reduce fluence differences between long Monte Carlo runs and perturbed mean runs; the correction accounts for statistical effects of time interpolation between model state updates. We have further implemented pre-release testing to evaluate the stability of the Monte Carlo results. Details on these changes may be found in Aerospace Report ATR-2016-00932 [1].

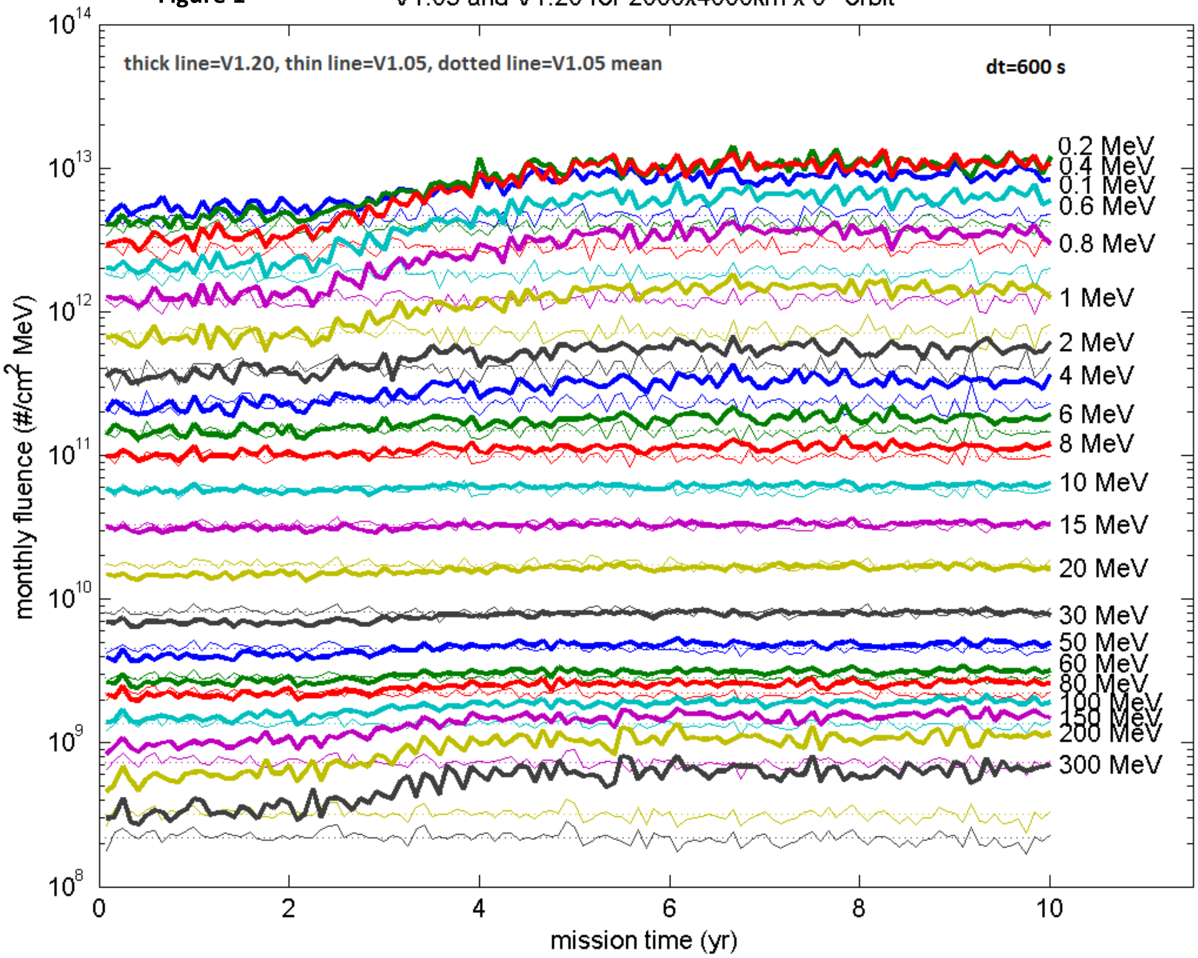
The practical effect is that cumulative statistics for long mission runs (>3-4 years) of AP9 V1.30 in Monte Carlo mode may differ significantly from such results for AP9 V1.20—specifically, cumulative statistics may be lower in V1.30, reflecting stable Monte Carlo behavior. Also, individual Monte Carlo scenario results in both AE9 and AP9 V1.30 will differ from those for the same scenarios in V1.20.

The issue described here did not affect mean, static percentile, or perturbed mean results for any of the models (AE9, AP9, and SPM); these results in V1.30 will be very similar to results from V1.20, with any small differences being the result of slight changes in handling of magnetic coordinate calculations (see AE9/AP9/SPM Radiation Environment Model Release Notes Version 1.30.001).

**Example of Monte Carlo instability in AP9 V1.20**

To illustrate the issue with AP9 V1.20, Figure 1 shows median AP9 monthly fluences from 40 Monte Carlo (MC) runs for V1.05 and V1.20. The changes in the V1.20 median after 2 years for energies less than ~6 MeV and greater than ~150 MeV result from the numerical instability. Note that initial medians are slightly different between V1.05 and V1.20 due to inclusion of new data and templates in V1.20.

**Figure 1**



**Verification of V1.30 fix to Monte Carlo issue**

The remaining figures illustrate test results showing the fix in V1.30 successfully addressed the issue: Figures 2-4 show results for AP9 and Figures 5-7 show results for AE9.

Figure 2 shows the 10 year fluence energy spectra based on 100 MC runs from V1.05, V1.20, and V1.30. The higher V1.20 fluences (compared to V1.05/V1.30), most noticable near 0.4 MeV and 300 MeV, result from the cumulative effect of the MC instability over the 10 year mission run. These V1.20 features are corrected in V1.30; the only change in the V1.30 maps relative to V1.20 is the correction of the MC numerical instability. The difference between V1.05 and V1.30 near 200 MeV represents the use of Van Allen Probe/RPS data-based templates first added in V1.20.

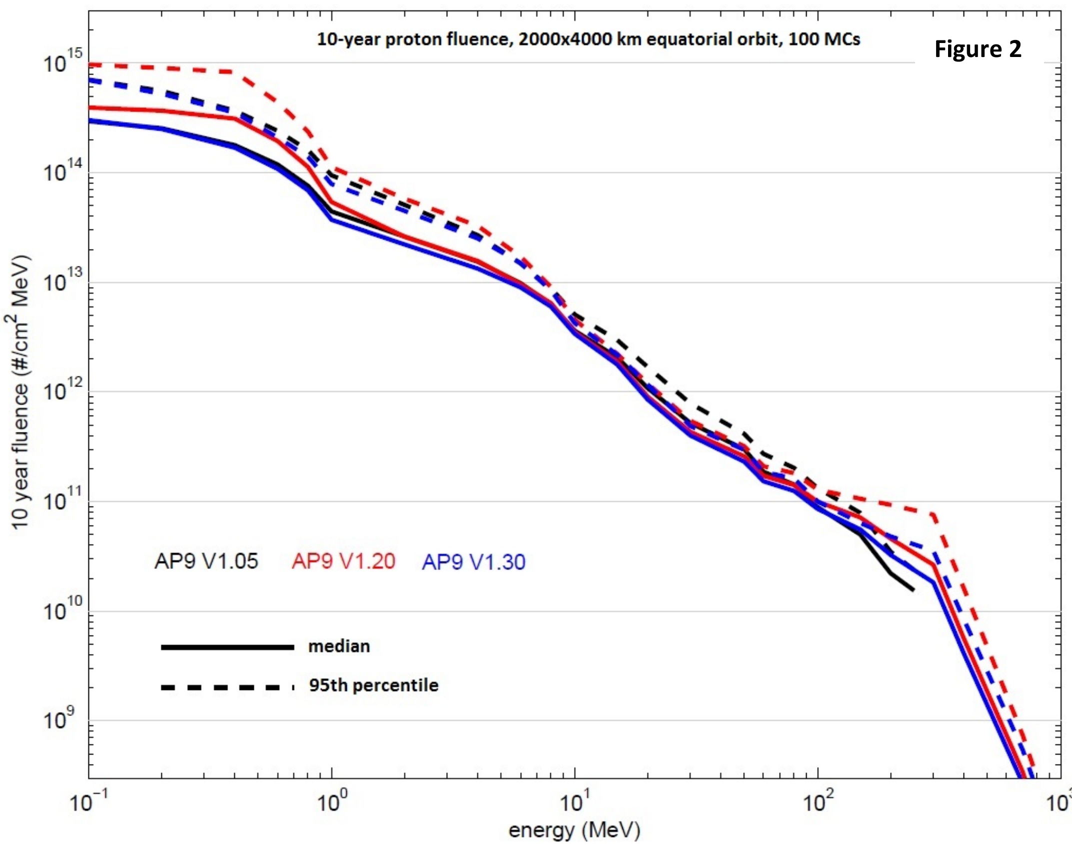
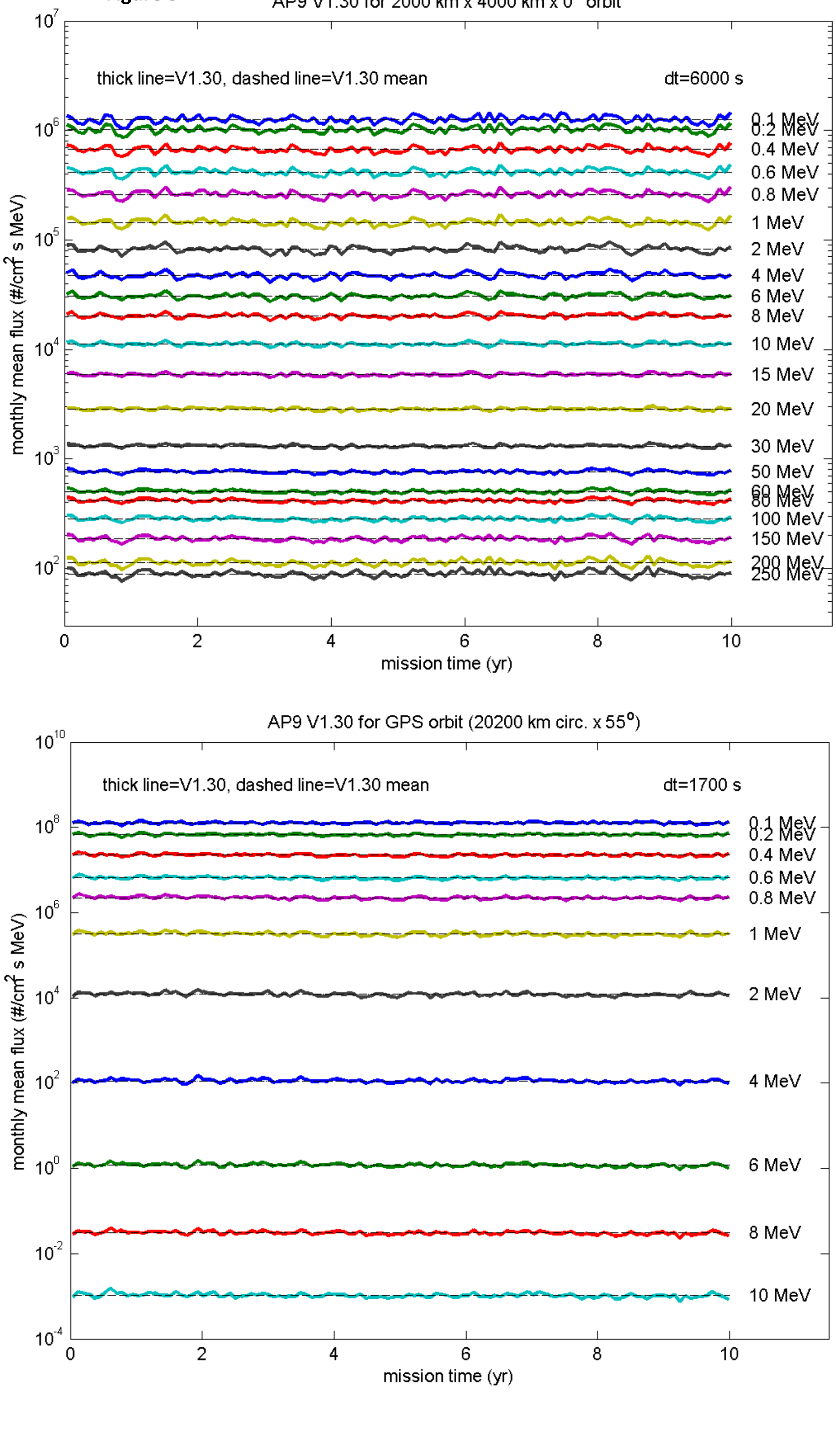



Figure 3 illustrates results of stability tests for AP9 V1.30. The top panel shows the monthly mean flux (30 day intervals) from AP9 V1.30 for a 10-year mission in the inner zone (2000 km x 4000 km equatorial orbit) based on 100 MC scenarios. The bottom panel shows a similar test for a GPS orbit (20200 km circular, 55° inclination) using AP9 V1.30 for a 10-year mission with 100 MC scenarios. In both plots the dashed lines show the MC mean, i.e. the mean at each energy for the full 10 years and 100 scenarios. Monthly mean fluxes remain stable throughout the mission in both tests.

**Figure 3**



AP9 V1.30 for 2000 km x 4000 km x 0° orbit
thick line=V1.30, dashed line=V1.30 mean
dt=6000 s
monthly mean flux (#/cm² s MeV)
mission time (yr)
0.1 MeV
0.2 MeV
0.4 MeV
0.6 MeV
0.8 MeV
1 MeV
2 MeV
4 MeV
6 MeV
8 MeV
10 MeV
15 MeV
20 MeV
30 MeV
50 MeV
60 MeV
80 MeV
100 MeV
150 MeV
200 MeV
250 MeV
AP9 V1.30 for GPS orbit (20200 km circ. x 55°)
thick line=V1.30, dashed line=V1.30 mean
dt=1700 s
monthly mean flux (#/cm² s MeV)
mission time (yr)
0.1 MeV
0.2 MeV
0.4 MeV
0.6 MeV
0.8 MeV
1 MeV
2 MeV
4 MeV
6 MeV
8 MeV
10 MeV

Figure 4 compares the annual fluence spectra for AP9 V1.20 and V1.30 from a 10-year mission (mean of 100 MC scenarios). Mean annual fluences are show by thin lines for the first year and thick lines for the full 10 years. The V1.20 annual mean fluences climb 1-2 orders of magnitude at low (<0.7 MeV) and high (>7 MeV) during the 10-year run due to the MC issue. In contrast, the first and full 10 year results from V1.30 are nearly identical except at the highest energy shown.

**Figure 4**

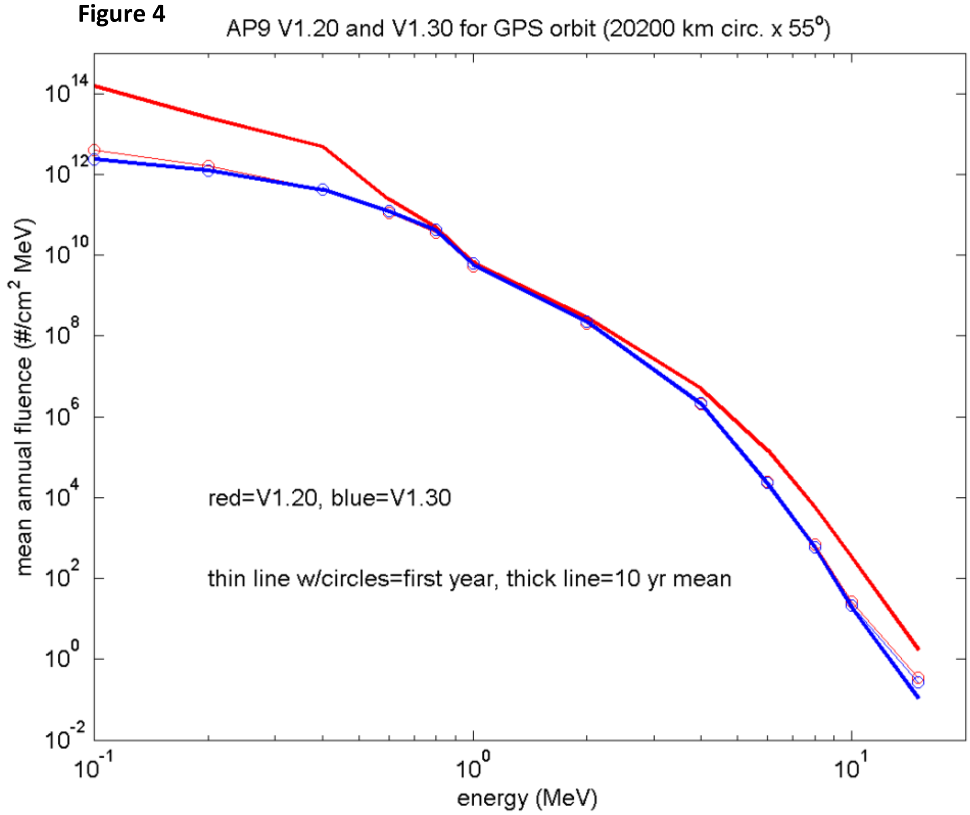


Figure 5 illustrates results of stability tests for AE9, showing monthly mean flux (30 day intervals) from AE9 V1.30 for a 9.5-year mission in the outer zone (15000 km x 25000 km equatorial orbit) based on 40 MC scenarios.  Monthly mean fluxes are stable throughout the test.

**Figure 5**

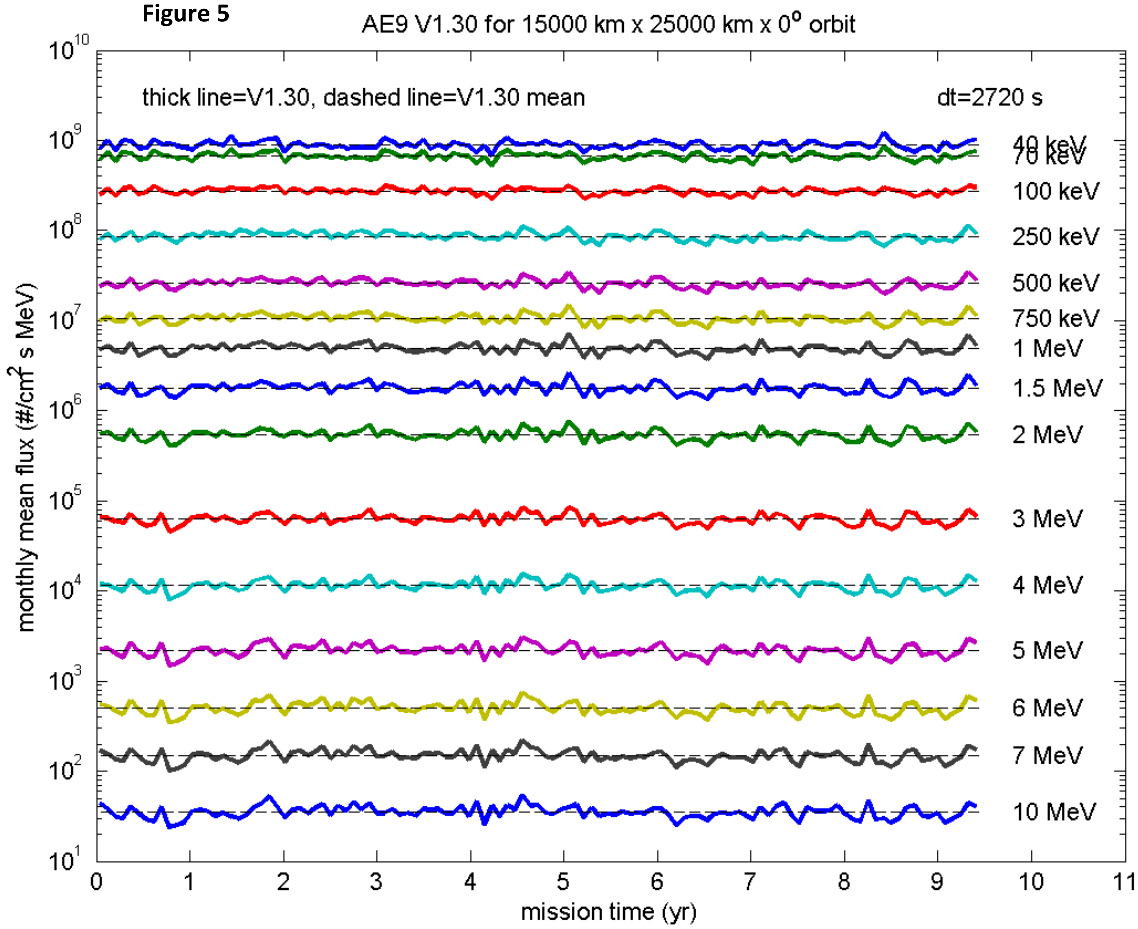
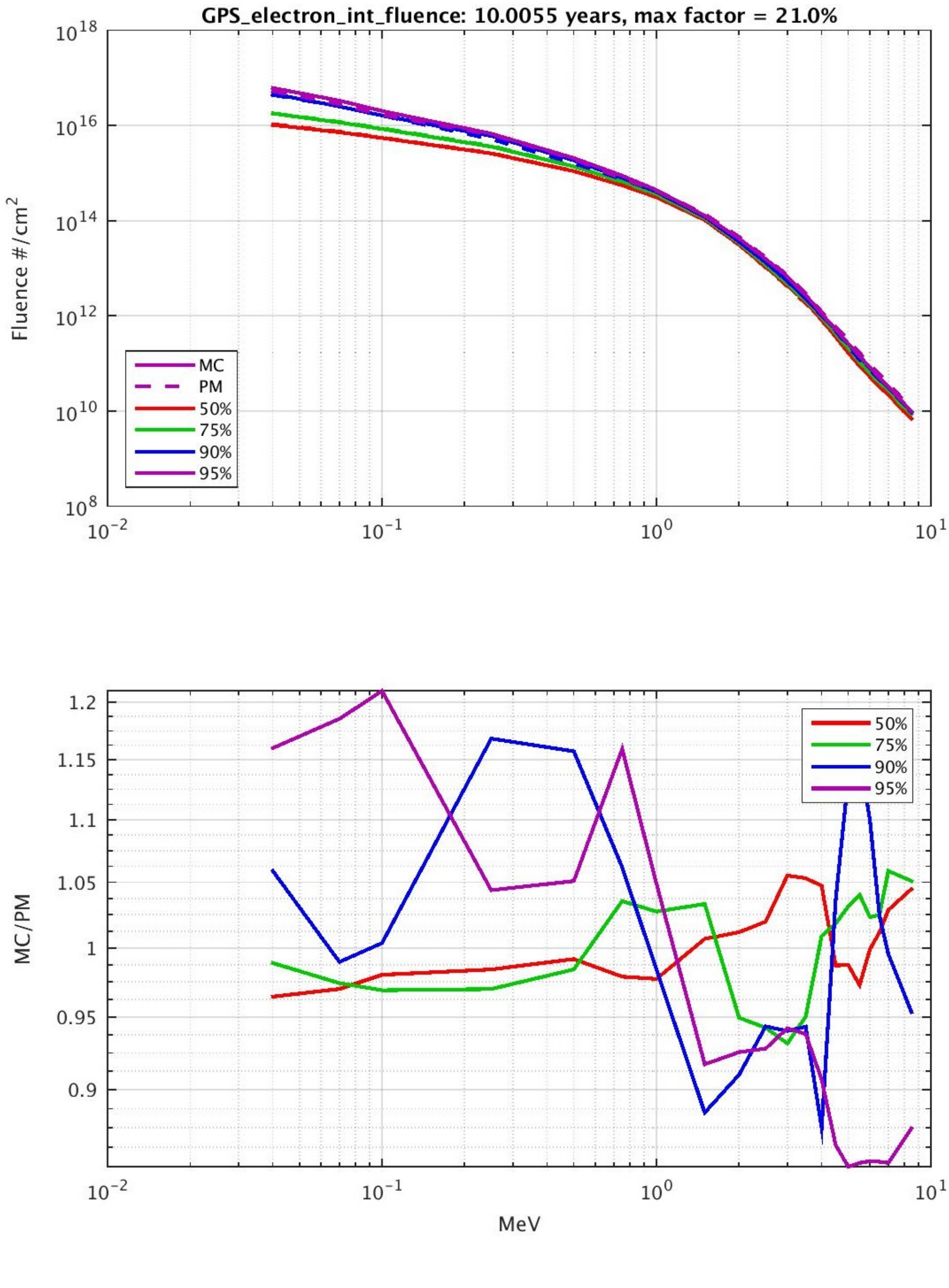


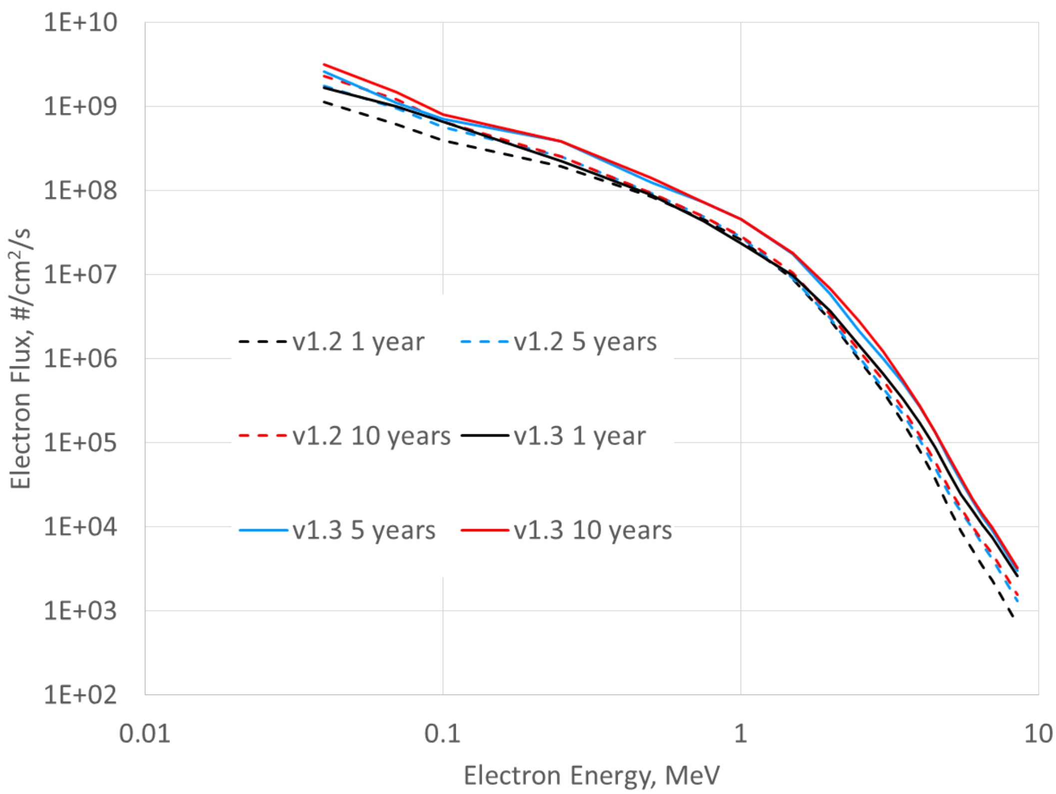

Figure 6 compares the MC and Perturbed Mean (PM) integral electron fluences for a 10-year GPS simulation in AE9 V1.30.  The colors are different percentiles, while the solid and dashed lines indicate the different run types (MC or PM).  The top panel shows the fluence spectrum, and the bottom panel shows the ratio of the MC fluence to the PM fluence at each percentile.  Over a range of common orbits, the V1.30 MC and PM fluences never differ by more than 33%.

**Figure 6**


GPS_electron_int_fluence: 10.0055 years, max factor = 21.0%
Fluence #/cm$^2$
MC
PM
50%
75%
90%
95%
MC/PM
MeV

Finally, Figure 7 shows a sample internal charging specification for different mission durations in a GPS orbit as derived from AE9 V1.2 and V1.3—specifically, the 95th percentile of the worst case 24-hour average electron flux based on 40 MC scenarios. The results based on V1.3 are 30-100% higher than those based on V1.2, indicating that the new version captures more of the flux variance than did the old version.

**Figure 7** 95th Percentile Worst Case 24-hour Average Electron Flux (GPS Orbit)




## References

[1] T. P. O'Brien and T. B. Guild, 2016, AE9/AP9 Monte Carlo upgrades (from V1.2 to V1.3), Aerospace Report ATR-2016-00932.