

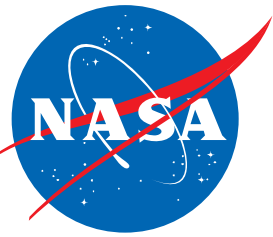
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# Total Dose Modeling of the Transit Through the Van Allen Belts

Thomas A. Carstens and Michael J. Campola

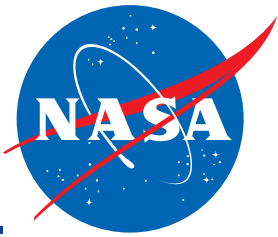
NASA GSFC, Code 561

5/25/2022



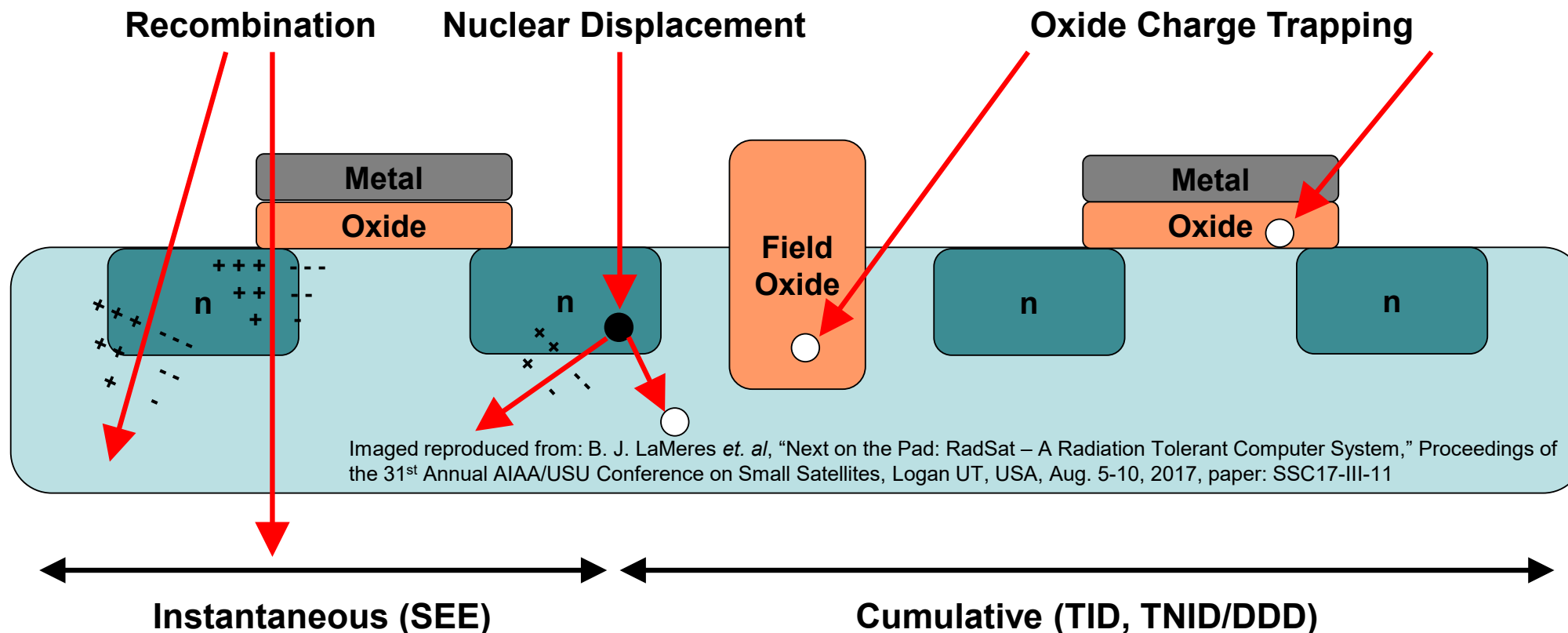
- Overview of Radiation Effects
- Space Radiation Environment
- Radiation Environment Modeling Tools
- Radiation Transport Modeling
- Radiation Belt Transfer Environments
  - Direct Transfer
  - GTO
  - Spiral
- Summary

# Acronyms



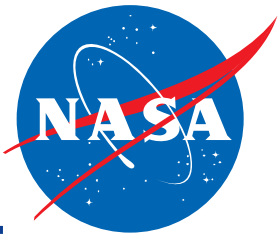
|       |                                                |       |                                          |
|-------|------------------------------------------------|-------|------------------------------------------|
| DDD   | Displacement Damage Dose                       | LEO   | Low Earth Orbit                          |
| ESA   | European Space Agency                          | MEO   | Middle Earth Orbit                       |
| GCR   | Galactic Cosmic Ray                            | NIEL  | Non-Ionizing Energy Loss                 |
| GEO   | Geosynchronous Orbit                           | SRREM | Slot Region Radiation Environment Models |
| GREEN | Global Radiation Earth ENvironment model       | SPE   | Solar Particle Event                     |
| GTO   | Geosynchronous Transfer Orbit                  | SPM   | Space Plasma Model                       |
| IRENE | International Radiation Environment Near-Earth | TID   | Total Ionizing Dose                      |
|       |                                                | TNID  | Total Nonionizing Dose                   |

# Overview of Radiation Effects



- Single Event Effects (SEE): instantaneous effect caused by a single ionizing particle
- Total Ionizing Dose (TID): cumulative degradation due to accumulation of trapped charge
- Total Non-Ionizing Dose (TNID)/Displacement Damage Dose (DDD): cumulative degradation due to accumulation of lattice defects

# Space Radiation Environment



- **Trapped Particle Environment**
  - Van Allen Belts
  - Proton and electron rich environment
  - TID, DDD
- **Solar Wind**
  - Protons, electrons, and heavy ions
  - Solar particle events
  - SEE, TID, DDD
- **Galactic Cosmic Rays (GCRs)**
  - Protons and heavy ions
  - SEEs
- **Plasma environment**
  - Spacecraft Charging

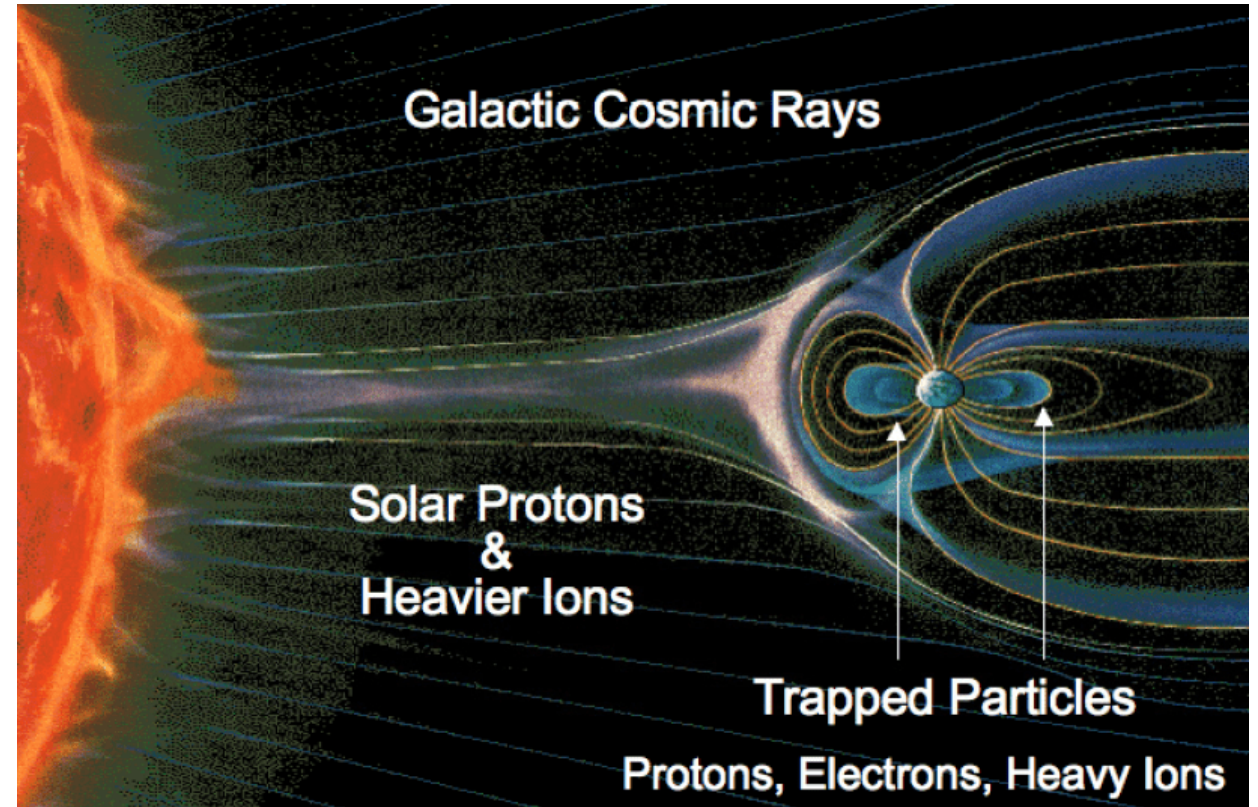
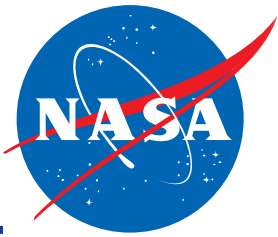


Image Credit: Nikkei Science, Inc. of Japan, image by K. Endo

# Radiation Environment Modeling Tools

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## Trapped particle fluences in Earth's radiation belts

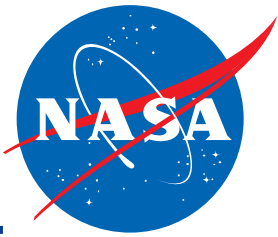
- AE-9 trapped electrons (IRENE)
- AP-9 trapped protons (IRENE)
- SPM
- AE8/AP8 older trapped particle models
- SRREM
- GREEN

## Solar proton fluences

- Emission of Solar Protons (ESP-PSYCHIC) Total Fluence
- JPL
- KING
- SAPPHIRE

# Radiation Transport Modeling

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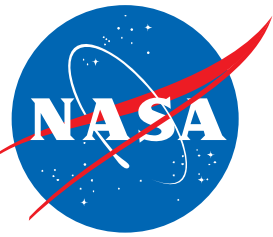


## **Radiation Transport Software:**

- SHIELDDOSE-2
- NOVICE
- FastRAD
- HZERT
- FLUKA
- Geant4
- MCNP

## **Space Environment Information System (SPENVIS):**

- Trapped particle environment
  - AE-9, AP-9, AE8, AP8, SRREM
  - No SPM
- Solar protons and solar cycle effects
  - ESP-PSYCHIC, King, JPL, SAPPHIRE
- Transport radiation environment through materials (TID, DDD dose-depth curves)
  - Uses SHIELDDOSE-2
- Funded by the European Space Agency (ESA)
- <https://www.spenvis.oma.be/intro.php>



# Radiation Environments – Transfer Orbits

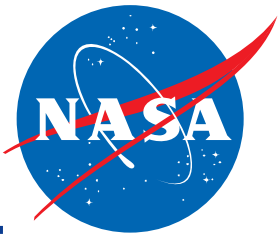
- Trajectory influences the amount of time spent in the Van Allen Belts
- Amount of time in belts affects the TID/DDD experienced by the electronics
- Initial orbit is critical; radiation risk is not 1:1 with trajectory duration

| Transfer Type         | Typical Duration | Benefits                   | Example Missions      |
|-----------------------|------------------|----------------------------|-----------------------|
| Direct, conventional  | 3 – 6 days       | Well known, quick          | Apollo, LRO           |
| Direct, staging       | 2 – 10 weeks     | Quick, many launch days    | Clementine, CH-1      |
| Direct to lunar $L_1$ | 1 – 5 weeks      | Staging at $L_1$           | None to date          |
| Low-thrust            | Many months      | Low fuel, many launch days | SMART-1               |
| Low-energy            | 2.5 – 4 months   | Low fuel, many launch days | Hiten, GRAIL, ARTEMIS |

Table reproduced from: J. S. Parker and R. L. Anderson, "Title of Chapter" in *Low-Energy Lunar Trajectory Design*, Pasadena, CA,: JPL, July 2013, Ch. 1, pp. 3.  
Available at: <https://descanso.jpl.nasa.gov/monograph/series12/LunarTraj--Overall.pdf>

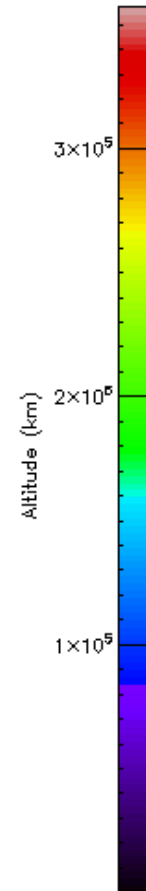
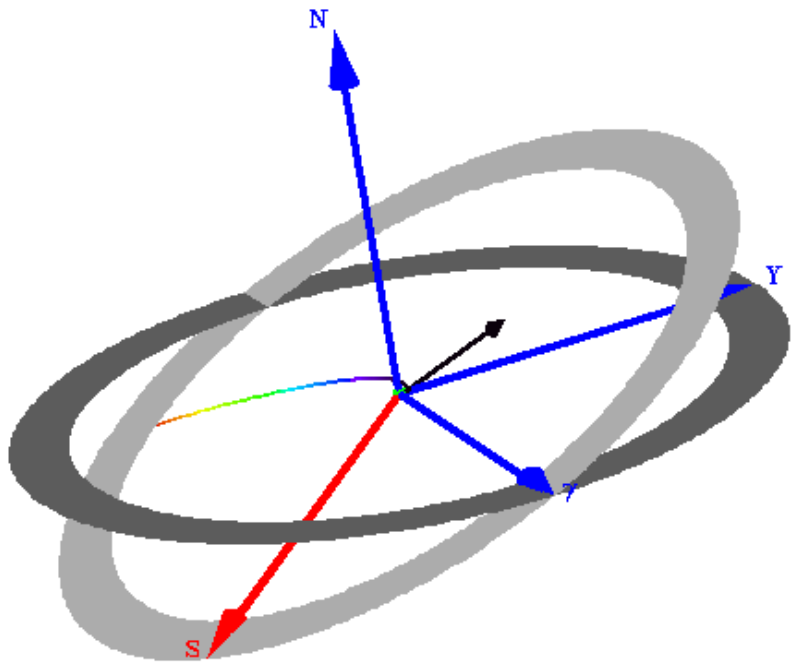
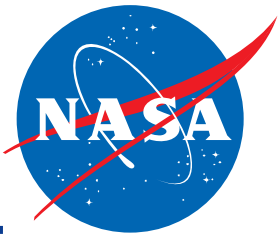
# Radiation Transit Modeling for Three Different Trajectories

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- Direct transfer
  - TID
  - DDD
- Geostationary transfer orbit
  - TID
  - DDD
- Spiral orbit
  - TID
  - DDD

# Direct Transfer (Earth to Moon)



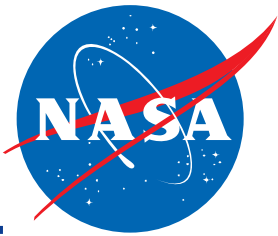
Trapped Protons: AP-9

Trapped Electrons: AE-9

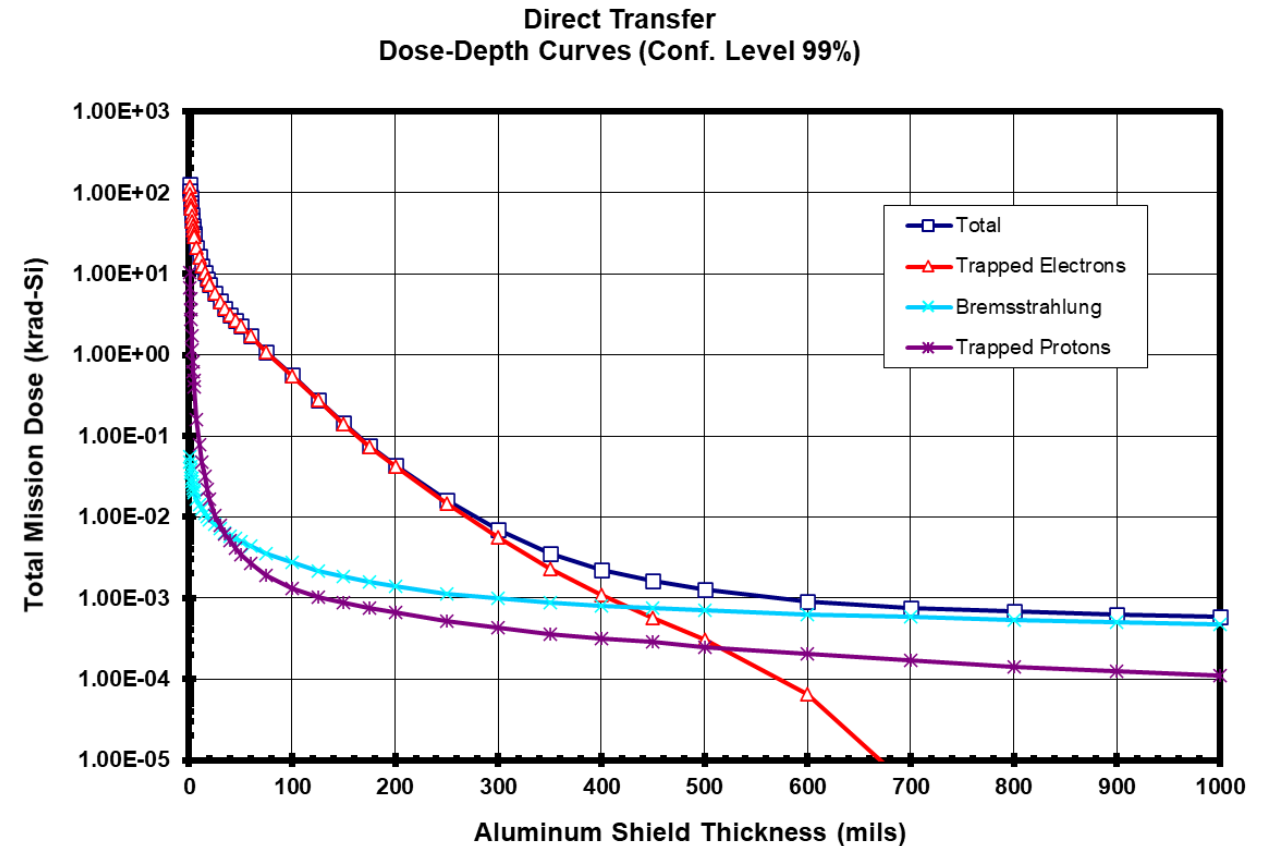
Solar Protons: Not included

Transport Model: Novice, adjoint  
solid sphere aluminum, Si target

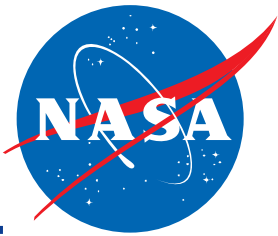
# Direct Transfer-Total Ionizing Dose from Van Allen Belts



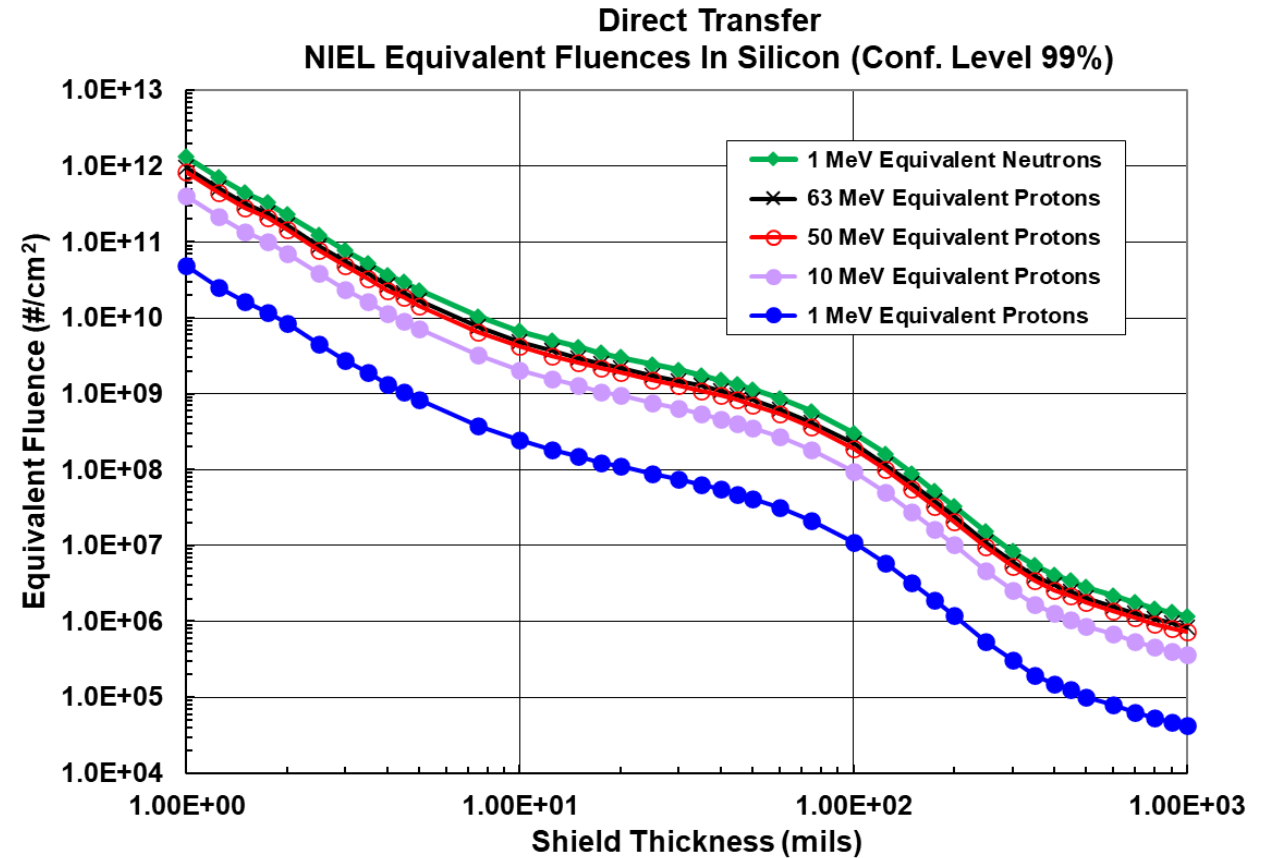
| Aluminum Shield Thickness |       |                   | Mission Dose (krad-Si) |          |          |          |
|---------------------------|-------|-------------------|------------------------|----------|----------|----------|
| mils                      | mm    | g/cm <sup>2</sup> | Total                  | Trap e   | Brem     | Trap p   |
| 1                         | 0.03  | 0.01              | 1.28E+02               | 1.18E+02 | 5.52E-02 | 1.04E+01 |
| 3                         | 0.08  | 0.02              | 4.56E+01               | 4.44E+01 | 2.72E-02 | 1.15E+00 |
| 10                        | 0.25  | 0.07              | 1.63E+01               | 1.62E+01 | 1.42E-02 | 7.91E-02 |
| 25                        | 0.63  | 0.17              | 5.76E+00               | 5.74E+00 | 8.06E-03 | 1.05E-02 |
| 50                        | 1.27  | 0.34              | 2.29E+00               | 2.28E+00 | 5.00E-03 | 3.41E-03 |
| 60                        | 1.52  | 0.41              | 1.70E+00               | 1.70E+00 | 4.34E-03 | 2.65E-03 |
| 75                        | 1.90  | 0.51              | 1.10E+00               | 1.10E+00 | 3.59E-03 | 1.92E-03 |
| 100                       | 2.54  | 0.69              | 5.59E-01               | 5.55E-01 | 2.74E-03 | 1.30E-03 |
| 125                       | 3.17  | 0.86              | 2.78E-01               | 2.74E-01 | 2.18E-03 | 1.04E-03 |
| 150                       | 3.81  | 1.03              | 1.43E-01               | 1.40E-01 | 1.82E-03 | 8.69E-04 |
| 200                       | 5.08  | 1.37              | 4.37E-02               | 4.17E-02 | 1.38E-03 | 6.60E-04 |
| 250                       | 6.35  | 1.71              | 1.63E-02               | 1.46E-02 | 1.14E-03 | 5.15E-04 |
| 300                       | 7.62  | 2.06              | 7.00E-03               | 5.59E-03 | 9.92E-04 | 4.25E-04 |
| 350                       | 8.89  | 2.40              | 3.58E-03               | 2.33E-03 | 8.91E-04 | 3.59E-04 |
| 400                       | 10.16 | 2.74              | 2.22E-03               | 1.10E-03 | 8.08E-04 | 3.16E-04 |
| 500                       | 12.70 | 3.43              | 1.27E-03               | 3.10E-04 | 7.06E-04 | 2.49E-04 |
| 600                       | 15.24 | 4.11              | 9.07E-04               | 6.56E-05 | 6.35E-04 | 2.06E-04 |
| 700                       | 17.78 | 4.80              | 7.57E-04               | 4.58E-06 | 5.83E-04 | 1.70E-04 |
| 800                       | 20.32 | 5.48              | 6.85E-04               | 2.58E-08 | 5.43E-04 | 1.43E-04 |
| 900                       | 22.86 | 6.17              | 6.28E-04               | 0.00E+00 | 5.03E-04 | 1.24E-04 |
| 1000                      | 25.40 | 6.86              | 5.81E-04               | 0.00E+00 | 4.70E-04 | 1.11E-04 |



# Direct Transfer-Displacement Damage Si from Van Allen Belts



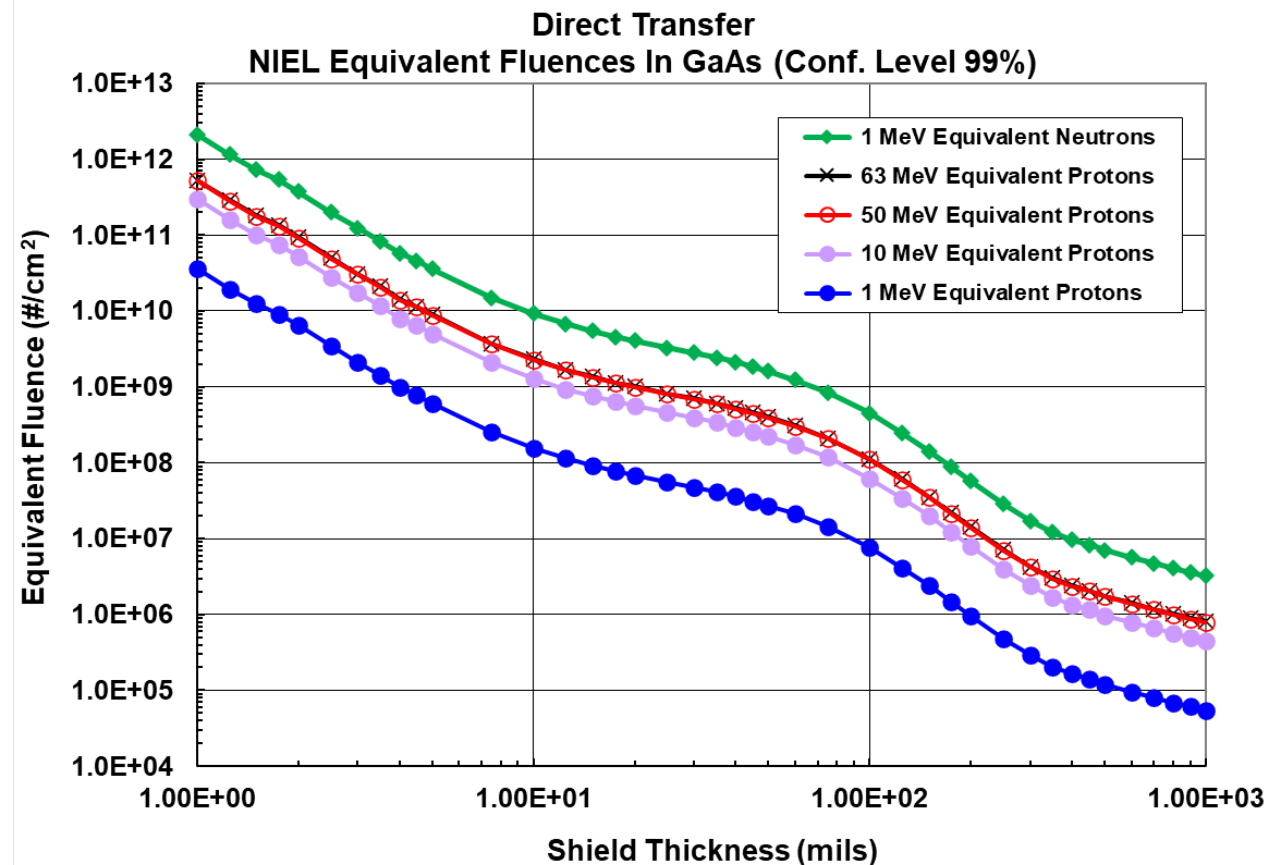
| NIEL Equivalent Fluences In Silicon    |          |                   |                         |                         |                          |                          |                          |
|----------------------------------------|----------|-------------------|-------------------------|-------------------------|--------------------------|--------------------------|--------------------------|
| Aluminum Solid-Sphere Shield Thickness |          |                   | 1 MeV n/cm <sup>2</sup> | 1 MeV p/cm <sup>2</sup> | 10 MeV p/cm <sup>2</sup> | 50 MeV p/cm <sup>2</sup> | 63 MeV p/cm <sup>2</sup> |
| mm                                     | mils     | g/cm <sup>2</sup> |                         |                         |                          |                          |                          |
| 2.54E-02                               | 1.00E+00 | 6.86E-03          | 1.337E+12               | 4.844E+10               | 4.132E+11                | 8.402E+11                | 9.674E+11                |
| 7.62E-02                               | 3.00E+00 | 2.06E-02          | 7.667E+10               | 2.779E+09               | 2.370E+10                | 4.820E+10                | 5.549E+10                |
| 2.54E-01                               | 1.00E+01 | 6.86E-02          | 6.724E+09               | 2.437E+08               | 2.079E+09                | 4.227E+09                | 4.866E+09                |
| 6.35E-01                               | 2.50E+01 | 1.71E-01          | 2.431E+09               | 8.811E+07               | 7.516E+08                | 1.528E+09                | 1.760E+09                |
| 1.27E+00                               | 5.00E+01 | 3.43E-01          | 1.140E+09               | 4.131E+07               | 3.523E+08                | 7.165E+08                | 8.249E+08                |
| 1.52E+00                               | 6.00E+01 | 4.11E-01          | 8.692E+08               | 3.150E+07               | 2.687E+08                | 5.464E+08                | 6.291E+08                |
| 1.90E+00                               | 7.50E+01 | 5.14E-01          | 5.863E+08               | 2.125E+07               | 1.812E+08                | 3.686E+08                | 4.243E+08                |
| 2.54E+00                               | 1.00E+02 | 6.86E-01          | 3.046E+08               | 1.104E+07               | 9.417E+07                | 1.915E+08                | 2.205E+08                |
| 3.17E+00                               | 1.25E+02 | 8.57E-01          | 1.603E+08               | 5.810E+06               | 4.956E+07                | 1.008E+08                | 1.160E+08                |
| 3.81E+00                               | 1.50E+02 | 1.03E+00          | 8.938E+07               | 3.239E+06               | 2.763E+07                | 5.619E+07                | 6.469E+07                |
| 5.08E+00                               | 2.00E+02 | 1.37E+00          | 3.325E+07               | 1.205E+06               | 1.028E+07                | 2.090E+07                | 2.407E+07                |
| 6.35E+00                               | 2.50E+02 | 1.71E+00          | 1.509E+07               | 5.468E+05               | 4.664E+06                | 9.485E+06                | 1.092E+07                |
| 7.62E+00                               | 3.00E+02 | 2.06E+00          | 8.405E+06               | 3.046E+05               | 2.598E+06                | 5.284E+06                | 6.083E+06                |
| 8.89E+00                               | 3.50E+02 | 2.40E+00          | 5.412E+06               | 1.961E+05               | 1.673E+06                | 3.402E+06                | 3.917E+06                |
| 1.02E+01                               | 4.00E+02 | 2.74E+00          | 4.141E+06               | 1.501E+05               | 1.280E+06                | 2.603E+06                | 2.997E+06                |
| 1.27E+01                               | 5.00E+02 | 3.43E+00          | 2.808E+06               | 1.018E+05               | 8.682E+05                | 1.765E+06                | 2.033E+06                |
| 1.52E+01                               | 6.00E+02 | 4.11E+00          | 2.177E+06               | 7.890E+04               | 6.730E+05                | 1.369E+06                | 1.576E+06                |
| 1.78E+01                               | 7.00E+02 | 4.80E+00          | 1.763E+06               | 6.389E+04               | 5.450E+05                | 1.108E+06                | 1.276E+06                |
| 2.03E+01                               | 8.00E+02 | 5.48E+00          | 1.484E+06               | 5.379E+04               | 4.588E+05                | 9.330E+05                | 1.074E+06                |
| 2.29E+01                               | 9.00E+02 | 6.17E+00          | 1.304E+06               | 4.725E+04               | 4.030E+05                | 8.196E+05                | 9.436E+05                |
| 2.54E+01                               | 1.00E+03 | 6.86E+00          | 1.168E+06               | 4.235E+04               | 3.612E+05                | 7.345E+05                | 8.457E+05                |



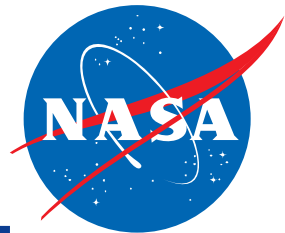
# Direct Transfer-Displacement Damage GaAs from Van Allen Belts



| NIEL Equivalent Fluences In Gallium Arsenide |           |                   |                         |                         |                          |                          |                          |
|----------------------------------------------|-----------|-------------------|-------------------------|-------------------------|--------------------------|--------------------------|--------------------------|
| Aluminum Solid-Sphere Shield Thickness       |           |                   | 1 MeV n/cm <sup>2</sup> | 1 MeV p/cm <sup>2</sup> | 10 MeV p/cm <sup>2</sup> | 50 MeV p/cm <sup>2</sup> | 63 MeV p/cm <sup>2</sup> |
| mm                                           | mils      | g/cm <sup>2</sup> |                         |                         |                          |                          |                          |
| 2.540E-02                                    | 1.000E+00 | 6.855E-03         | 2.123E+12               | 3.611E+10               | 2.959E+11                | 5.200E+11                | 5.308E+11                |
| 7.620E-02                                    | 3.000E+00 | 2.057E-02         | 1.241E+11               | 2.111E+09               | 1.730E+10                | 3.040E+10                | 3.103E+10                |
| 2.540E-01                                    | 1.000E+01 | 6.855E-02         | 9.244E+09               | 1.572E+08               | 1.288E+09                | 2.264E+09                | 2.311E+09                |
| 6.350E-01                                    | 2.500E+01 | 1.714E-01         | 3.266E+09               | 5.556E+07               | 4.552E+08                | 8.000E+08                | 8.165E+08                |
| 1.270E+00                                    | 5.000E+01 | 3.428E-01         | 1.611E+09               | 2.741E+07               | 2.246E+08                | 3.947E+08                | 4.028E+08                |
| 1.524E+00                                    | 6.000E+01 | 4.113E-01         | 1.241E+09               | 2.111E+07               | 1.730E+08                | 3.040E+08                | 3.103E+08                |
| 1.905E+00                                    | 7.500E+01 | 5.141E-01         | 8.503E+08               | 1.446E+07               | 1.185E+08                | 2.083E+08                | 2.126E+08                |
| 2.540E+00                                    | 1.000E+02 | 6.855E-01         | 4.486E+08               | 7.630E+06               | 6.252E+07                | 1.099E+08                | 1.121E+08                |
| 3.175E+00                                    | 1.250E+02 | 8.569E-01         | 2.439E+08               | 4.148E+06               | 3.399E+07                | 5.973E+07                | 6.097E+07                |
| 3.810E+00                                    | 1.500E+02 | 1.028E+00         | 1.415E+08               | 2.407E+06               | 1.973E+07                | 3.467E+07                | 3.538E+07                |
| 5.080E+00                                    | 2.000E+02 | 1.371E+00         | 5.738E+07               | 9.759E+05               | 7.997E+06                | 1.405E+07                | 1.434E+07                |
| 6.350E+00                                    | 2.500E+02 | 1.714E+00         | 2.842E+07               | 4.833E+05               | 3.961E+06                | 6.960E+06                | 7.104E+06                |
| 7.620E+00                                    | 3.000E+02 | 2.057E+00         | 1.720E+07               | 2.926E+05               | 2.398E+06                | 4.213E+06                | 4.300E+06                |
| 8.890E+00                                    | 3.500E+02 | 2.399E+00         | 1.209E+07               | 2.056E+05               | 1.684E+06                | 2.960E+06                | 3.021E+06                |
| 1.016E+01                                    | 4.000E+02 | 2.742E+00         | 9.690E+06               | 1.648E+05               | 1.351E+06                | 2.373E+06                | 2.422E+06                |
| 1.270E+01                                    | 5.000E+02 | 3.428E+00         | 6.990E+06               | 1.189E+05               | 9.742E+05                | 1.712E+06                | 1.747E+06                |
| 1.524E+01                                    | 6.000E+02 | 4.113E+00         | 5.640E+06               | 9.593E+04               | 7.860E+05                | 1.381E+06                | 1.410E+06                |
| 1.778E+01                                    | 7.000E+02 | 4.799E+00         | 4.714E+06               | 8.019E+04               | 6.571E+05                | 1.155E+06                | 1.179E+06                |
| 2.032E+01                                    | 8.000E+02 | 5.484E+00         | 4.050E+06               | 6.889E+04               | 5.645E+05                | 9.920E+05                | 1.013E+06                |
| 2.286E+01                                    | 9.000E+02 | 6.170E+00         | 3.593E+06               | 6.111E+04               | 5.008E+05                | 8.800E+05                | 8.982E+05                |
| 2.540E+01                                    | 1.000E+03 | 6.855E+00         | 3.223E+06               | 5.481E+04               | 4.492E+05                | 7.893E+05                | 8.057E+05                |



# Geostationary Transfer Orbit (GTO)



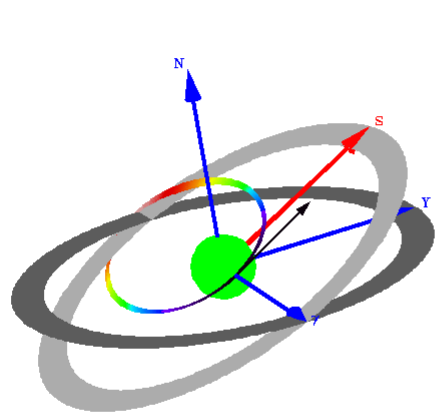
| Orbital Phase Number         | 1     | 2     | 3     |
|------------------------------|-------|-------|-------|
| Apogee (km)                  | 35790 | 35810 | 35828 |
| Perigee (km)                 | 188   | 10188 | 33194 |
| Angle of Inclination         | 28.7° | 28.7° | 28.7° |
| Period of Revolution (hours) | 10.51 | 13.91 | 22.85 |

Trapped Protons: AP-9

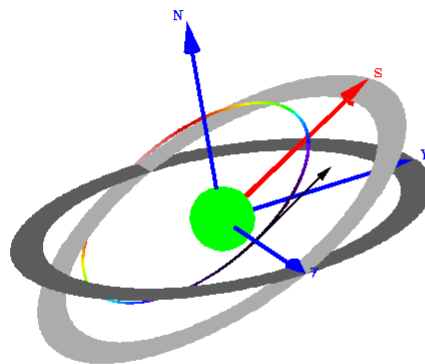
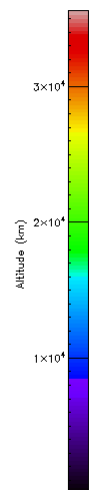
Trapped Electrons: AE-9

Solar Protons: Not included

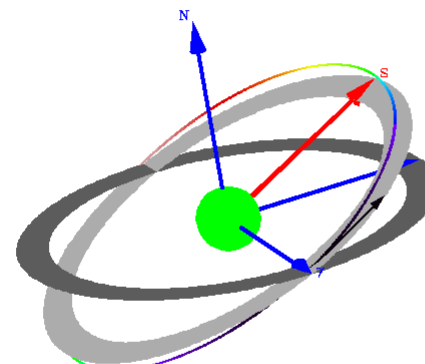
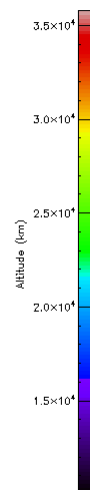
Transport Model: Novice, adjoint solid sphere aluminum, Si target



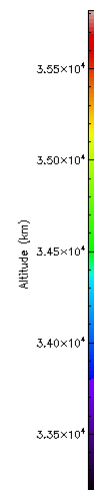
Phase 1



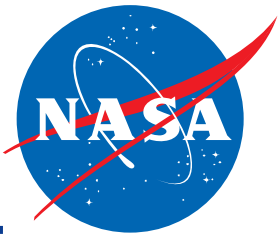
Phase 2



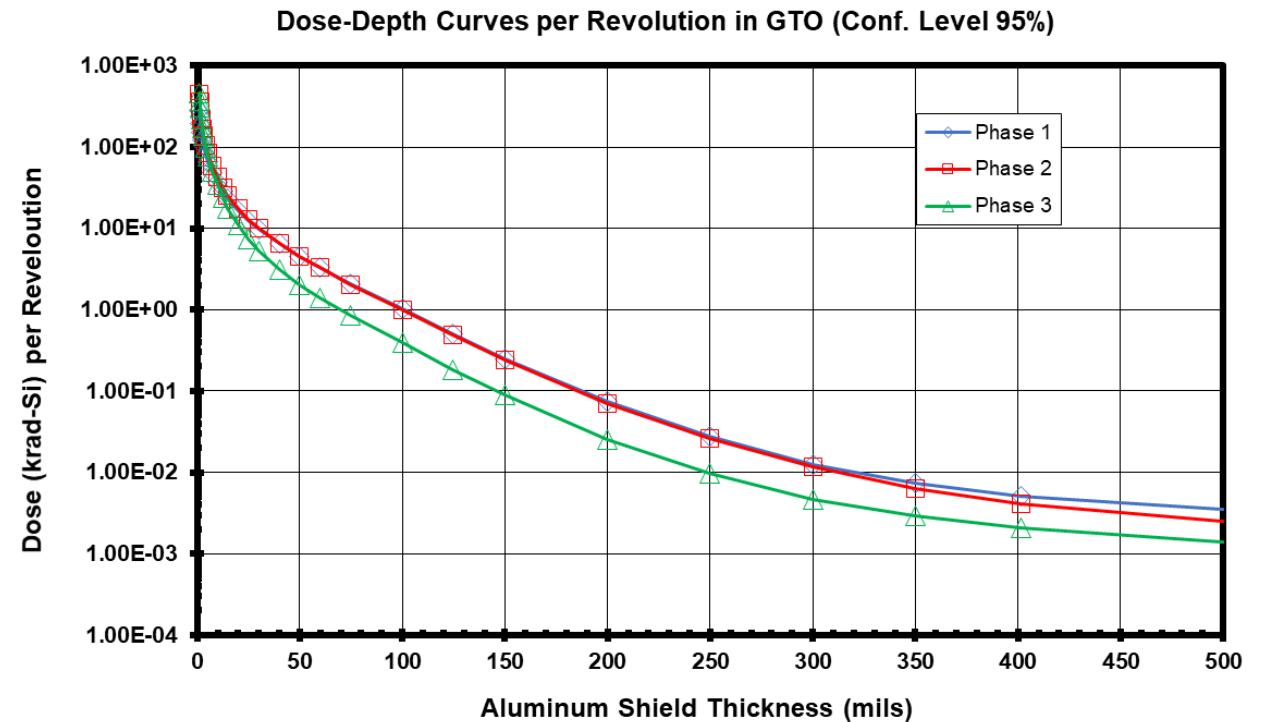
Phase 3



# GTO-Total Ionizing Dose from Van Allen Belts



| Aluminum Shield Thickness |       |                   | Dose (krad-Si/Rev) |          |          |
|---------------------------|-------|-------------------|--------------------|----------|----------|
| mils                      | mm    | g/cm <sup>2</sup> | Phase 1            | Phase 2  | Phase 3  |
| 1                         | 0.03  | 0.01              | 2.83E+02           | 4.53E+02 | 4.67E+02 |
| 3                         | 0.08  | 0.02              | 1.04E+02           | 1.38E+02 | 1.37E+02 |
| 10                        | 0.25  | 0.07              | 3.70E+01           | 4.26E+01 | 3.42E+01 |
| 25                        | 0.63  | 0.17              | 1.25E+01           | 1.30E+01 | 7.43E+00 |
| 50                        | 1.27  | 0.34              | 4.57E+00           | 4.51E+00 | 2.03E+00 |
| 60                        | 1.52  | 0.41              | 3.34E+00           | 3.27E+00 | 1.40E+00 |
| 75                        | 1.90  | 0.51              | 2.10E+00           | 2.05E+00 | 8.43E-01 |
| 100                       | 2.54  | 0.69              | 1.04E+00           | 1.01E+00 | 3.91E-01 |
| 125                       | 3.17  | 0.86              | 5.02E-01           | 4.84E-01 | 1.83E-01 |
| 150                       | 3.81  | 1.03              | 2.52E-01           | 2.41E-01 | 8.92E-02 |
| 200                       | 5.08  | 1.37              | 7.39E-02           | 7.08E-02 | 2.54E-02 |
| 250                       | 6.35  | 1.71              | 2.74E-02           | 2.60E-02 | 9.60E-03 |
| 300                       | 7.62  | 2.06              | 1.26E-02           | 1.16E-02 | 4.70E-03 |
| 350                       | 8.89  | 2.40              | 7.28E-03           | 6.30E-03 | 2.90E-03 |
| 400                       | 10.16 | 2.74              | 5.15E-03           | 4.14E-03 | 2.08E-03 |
| 500                       | 12.70 | 3.43              | 3.50E-03           | 2.52E-03 | 1.37E-03 |
| 600                       | 15.24 | 4.11              | 2.76E-03           | 1.84E-03 | 1.04E-03 |
| 700                       | 17.78 | 4.80              | 2.34E-03           | 1.51E-03 | 8.58E-04 |
| 800                       | 20.32 | 5.48              | 2.04E-03           | 1.32E-03 | 7.43E-04 |
| 900                       | 22.86 | 6.17              | 1.85E-03           | 1.19E-03 | 6.70E-04 |
| 1000                      | 25.40 | 6.86              | 1.70E-03           | 1.11E-03 | 6.13E-04 |



# GTO-Displacement Damage Si from Van Allen Belts



NIEL Equivalent Fluences in Silicon for Phase 1 (Conf. Level 95%)

| Aluminum Solid-Sphere Shield Thickness |         |                   | 1 MeV Equivalent Proton Fluence<br>#/cm <sup>2</sup> per Rev | 10 MeV Equivalent Proton Fluence<br>#/cm <sup>2</sup> per Rev | 50 MeV Equivalent Proton Fluence<br>#/cm <sup>2</sup> per Rev | 63 MeV Equivalent Proton Fluence<br>#/cm <sup>2</sup> per Rev | 1 MeV Equivalent Neutron Fluence<br>#/cm <sup>2</sup> per Rev |
|----------------------------------------|---------|-------------------|--------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| mils                                   | mm      | g/cm <sup>2</sup> |                                                              |                                                               |                                                               |                                                               |                                                               |
| 1                                      | 0.0254  | 0.00686           | 1.136E+11                                                    | 9.686E+11                                                     | 1.970E+12                                                     | 2.268E+12                                                     | 3.133E+12                                                     |
| 3                                      | 0.0762  | 0.02057           | 7.220E+09                                                    | 6.159E+10                                                     | 1.252E+11                                                     | 1.442E+11                                                     | 1.992E+11                                                     |
| 10                                     | 0.2540  | 0.06855           | 6.043E+08                                                    | 5.155E+09                                                     | 1.048E+10                                                     | 1.207E+10                                                     | 1.668E+10                                                     |
| 25                                     | 0.6350  | 0.17138           | 1.908E+08                                                    | 1.627E+09                                                     | 3.309E+09                                                     | 3.809E+09                                                     | 5.263E+09                                                     |
| 50                                     | 1.2700  | 0.34276           | 8.307E+07                                                    | 7.086E+08                                                     | 1.441E+09                                                     | 1.659E+09                                                     | 2.292E+09                                                     |
| 60                                     | 1.5240  | 0.41131           | 6.240E+07                                                    | 5.322E+08                                                     | 1.082E+09                                                     | 1.246E+09                                                     | 1.722E+09                                                     |
| 75                                     | 1.9050  | 0.51414           | 4.154E+07                                                    | 3.543E+08                                                     | 7.205E+08                                                     | 8.295E+08                                                     | 1.146E+09                                                     |
| 100                                    | 2.5400  | 0.68552           | 2.121E+07                                                    | 1.810E+08                                                     | 3.680E+08                                                     | 4.237E+08                                                     | 5.854E+08                                                     |
| 125                                    | 3.1750  | 0.85690           | 1.127E+07                                                    | 9.610E+07                                                     | 1.954E+08                                                     | 2.250E+08                                                     | 3.109E+08                                                     |
| 150                                    | 3.8100  | 1.02828           | 6.436E+06                                                    | 5.489E+07                                                     | 1.116E+08                                                     | 1.285E+08                                                     | 1.776E+08                                                     |
| 200                                    | 5.0800  | 1.37104           | 2.674E+06                                                    | 2.281E+07                                                     | 4.638E+07                                                     | 5.340E+07                                                     | 7.378E+07                                                     |
| 250                                    | 6.3500  | 1.71380           | 1.467E+06                                                    | 1.251E+07                                                     | 2.545E+07                                                     | 2.930E+07                                                     | 4.048E+07                                                     |
| 300                                    | 7.6200  | 2.05656           | 1.014E+06                                                    | 8.652E+06                                                     | 1.759E+07                                                     | 2.026E+07                                                     | 2.799E+07                                                     |
| 350                                    | 8.8900  | 2.39932           | 7.844E+05                                                    | 6.691E+06                                                     | 1.361E+07                                                     | 1.566E+07                                                     | 2.164E+07                                                     |
| 400                                    | 10.1600 | 2.74208           | 6.721E+05                                                    | 5.733E+06                                                     | 1.166E+07                                                     | 1.342E+07                                                     | 1.854E+07                                                     |
| 500                                    | 12.7000 | 3.42760           | 5.295E+05                                                    | 4.516E+06                                                     | 9.184E+06                                                     | 1.057E+07                                                     | 1.461E+07                                                     |
| 600                                    | 15.2400 | 4.11312           | 4.475E+05                                                    | 3.817E+06                                                     | 7.761E+06                                                     | 8.936E+06                                                     | 1.235E+07                                                     |
| 700                                    | 17.7800 | 4.79864           | 3.851E+05                                                    | 3.285E+06                                                     | 6.679E+06                                                     | 7.690E+06                                                     | 1.063E+07                                                     |
| 800                                    | 20.3200 | 5.48416           | 3.334E+05                                                    | 2.844E+06                                                     | 5.782E+06                                                     | 6.657E+06                                                     | 9.199E+06                                                     |
| 900                                    | 22.8600 | 6.16969           | 3.031E+05                                                    | 2.585E+06                                                     | 5.257E+06                                                     | 6.052E+06                                                     | 8.362E+06                                                     |
| 1000                                   | 25.4000 | 6.85521           | 2.799E+05                                                    | 2.387E+06                                                     | 4.855E+06                                                     | 5.589E+06                                                     | 7.723E+06                                                     |

NIEL Equivalent Fluences in Silicon for Phase 2 (Conf. Level 95%)

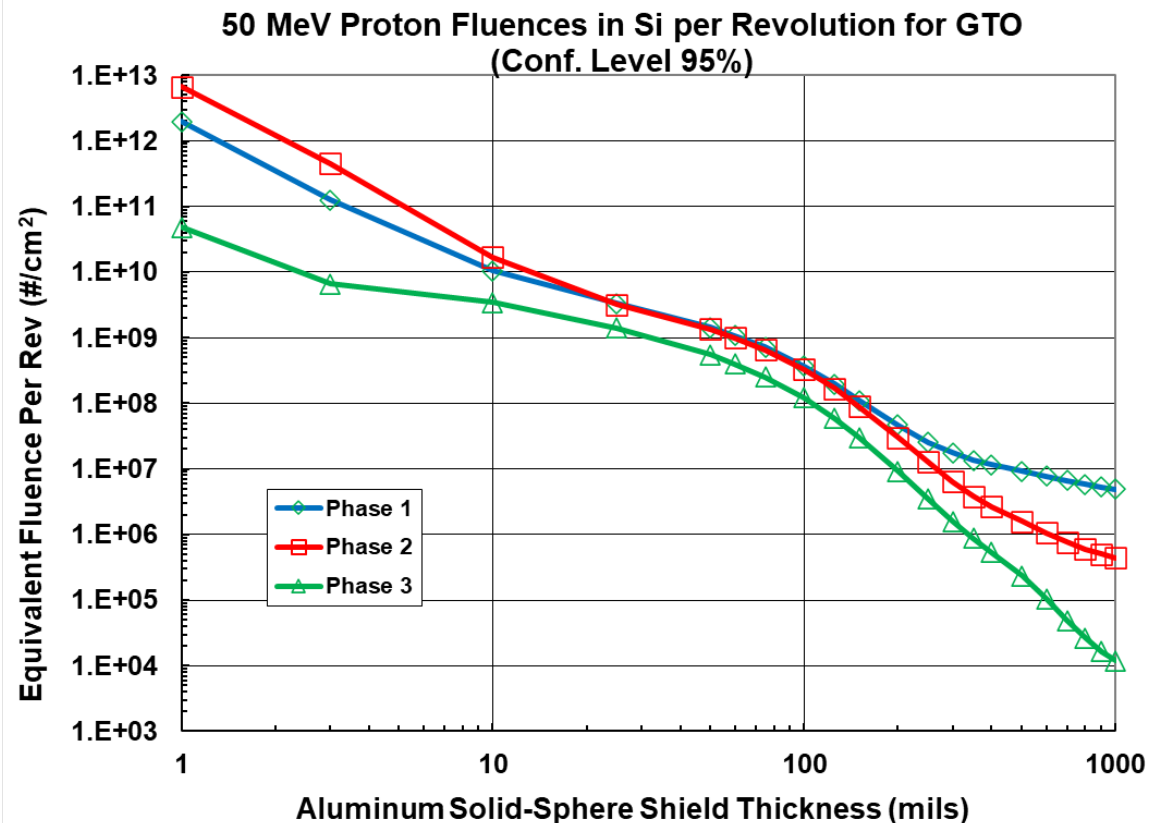
| Aluminum Solid-Sphere Shield Thickness |         |                   | 1 MeV Equivalent Proton Fluence<br>#/cm <sup>2</sup> per Rev | 10 MeV Equivalent Proton Fluence<br>#/cm <sup>2</sup> per Rev | 50 MeV Equivalent Proton Fluence<br>#/cm <sup>2</sup> per Rev | 63 MeV Equivalent Proton Fluence<br>#/cm <sup>2</sup> per Rev | 1 MeV Equivalent Neutron Fluence<br>#/cm <sup>2</sup> per Rev |
|----------------------------------------|---------|-------------------|--------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| mils                                   | mm      | g/cm <sup>2</sup> |                                                              |                                                               |                                                               |                                                               |                                                               |
| 1                                      | 0.0254  | 0.00686           | 3.893E+11                                                    | 3.321E+12                                                     | 6.753E+12                                                     | 7.775E+12                                                     | 1.074E+13                                                     |
| 3                                      | 0.0762  | 0.02057           | 2.619E+10                                                    | 2.234E+11                                                     | 4.543E+11                                                     | 5.230E+11                                                     | 7.226E+11                                                     |
| 10                                     | 0.2540  | 0.06855           | 9.697E+08                                                    | 8.272E+09                                                     | 1.682E+10                                                     | 1.937E+10                                                     | 2.676E+10                                                     |
| 25                                     | 0.6350  | 0.17138           | 1.855E+08                                                    | 1.582E+09                                                     | 3.217E+09                                                     | 3.704E+09                                                     | 5.117E+09                                                     |
| 50                                     | 1.2700  | 0.34276           | 7.786E+07                                                    | 6.641E+08                                                     | 1.351E+09                                                     | 1.555E+09                                                     | 2.148E+09                                                     |
| 60                                     | 1.5240  | 0.41131           | 5.781E+07                                                    | 4.931E+08                                                     | 1.003E+09                                                     | 1.154E+09                                                     | 1.595E+09                                                     |
| 75                                     | 1.9050  | 0.51414           | 3.799E+07                                                    | 3.240E+08                                                     | 6.589E+08                                                     | 7.586E+08                                                     | 1.048E+09                                                     |
| 100                                    | 2.5400  | 0.68552           | 1.904E+07                                                    | 1.624E+08                                                     | 3.303E+08                                                     | 3.802E+08                                                     | 5.254E+08                                                     |
| 125                                    | 3.1750  | 0.85690           | 9.650E+06                                                    | 8.231E+07                                                     | 1.674E+08                                                     | 1.927E+08                                                     | 2.663E+08                                                     |
| 150                                    | 3.8100  | 1.02828           | 5.144E+06                                                    | 4.387E+07                                                     | 8.922E+07                                                     | 1.027E+08                                                     | 1.419E+08                                                     |
| 200                                    | 5.0800  | 1.37104           | 1.748E+06                                                    | 1.491E+07                                                     | 3.033E+07                                                     | 3.491E+07                                                     | 4.824E+07                                                     |
| 250                                    | 6.3500  | 1.71380           | 7.291E+05                                                    | 6.219E+06                                                     | 1.265E+07                                                     | 1.456E+07                                                     | 2.012E+07                                                     |
| 300                                    | 7.6200  | 2.05656           | 3.704E+05                                                    | 3.160E+06                                                     | 6.425E+06                                                     | 7.398E+06                                                     | 1.022E+07                                                     |
| 350                                    | 8.8900  | 2.39932           | 2.199E+05                                                    | 1.876E+06                                                     | 3.814E+06                                                     | 4.391E+06                                                     | 6.068E+06                                                     |
| 400                                    | 10.1600 | 2.74208           | 1.536E+05                                                    | 1.310E+06                                                     | 2.664E+06                                                     | 3.067E+06                                                     | 4.238E+06                                                     |
| 500                                    | 12.7000 | 3.42760           | 9.060E+04                                                    | 7.728E+05                                                     | 1.572E+06                                                     | 1.809E+06                                                     | 2.500E+06                                                     |
| 600                                    | 15.2400 | 4.11312           | 6.158E+04                                                    | 5.253E+05                                                     | 1.068E+06                                                     | 1.230E+06                                                     | 1.699E+06                                                     |
| 700                                    | 17.7800 | 4.79864           | 4.459E+04                                                    | 3.804E+05                                                     | 7.735E+05                                                     | 8.905E+05                                                     | 1.230E+06                                                     |
| 800                                    | 20.3200 | 5.48416           | 3.445E+04                                                    | 2.938E+05                                                     | 5.975E+05                                                     | 6.879E+05                                                     | 9.505E+05                                                     |
| 900                                    | 22.8600 | 6.16969           | 2.926E+04                                                    | 2.496E+05                                                     | 5.075E+05                                                     | 5.843E+05                                                     | 8.073E+05                                                     |
| 1000                                   | 25.4000 | 6.85521           | 2.525E+04                                                    | 2.153E+05                                                     | 4.379E+05                                                     | 5.042E+05                                                     | 6.966E+05                                                     |

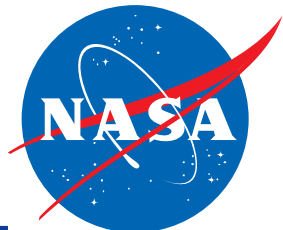
# GTO-Displacement Damage Si from Van Allen Belts



NIEL Equivalent Fluences in Silicon for Phase 3 (Conf. Level 95%)

| Aluminum Solid-Sphere Shield Thickness |         |                   | 1 MeV Equivalent Proton Fluence #/cm <sup>2</sup> per Rev | 10 MeV Equivalent Proton Fluence #/cm <sup>2</sup> per Rev | 50 MeV Equivalent Proton Fluence #/cm <sup>2</sup> per Rev | 63 MeV Equivalent Proton Fluence #/cm <sup>2</sup> per Rev | 1 MeV Equivalent Neutron Fluence #/cm <sup>2</sup> per Rev |
|----------------------------------------|---------|-------------------|-----------------------------------------------------------|------------------------------------------------------------|------------------------------------------------------------|------------------------------------------------------------|------------------------------------------------------------|
| mils                                   | mm      | g/cm <sup>2</sup> |                                                           |                                                            |                                                            |                                                            |                                                            |
| 1                                      | 0.0254  | 0.00686           | 2.767E+09                                                 | 2.360E+10                                                  | 4.800E+10                                                  | 5.527E+10                                                  | 7.636E+10                                                  |
| 3                                      | 0.0762  | 0.02057           | 3.837E+08                                                 | 3.273E+09                                                  | 6.656E+09                                                  | 7.663E+09                                                  | 1.059E+10                                                  |
| 10                                     | 0.2540  | 0.06855           | 1.981E+08                                                 | 1.689E+09                                                  | 3.435E+09                                                  | 3.955E+09                                                  | 5.465E+09                                                  |
| 25                                     | 0.6350  | 0.17138           | 8.178E+07                                                 | 6.976E+08                                                  | 1.419E+09                                                  | 1.633E+09                                                  | 2.257E+09                                                  |
| 50                                     | 1.2700  | 0.34276           | 3.151E+07                                                 | 2.688E+08                                                  | 5.466E+08                                                  | 6.293E+08                                                  | 8.695E+08                                                  |
| 60                                     | 1.5240  | 0.41131           | 2.287E+07                                                 | 1.951E+08                                                  | 3.966E+08                                                  | 4.567E+08                                                  | 6.310E+08                                                  |
| 75                                     | 1.9050  | 0.51414           | 1.453E+07                                                 | 1.240E+08                                                  | 2.521E+08                                                  | 2.903E+08                                                  | 4.010E+08                                                  |
| 100                                    | 2.5400  | 0.68552           | 6.977E+06                                                 | 5.951E+07                                                  | 1.210E+08                                                  | 1.393E+08                                                  | 1.925E+08                                                  |
| 125                                    | 3.1750  | 0.85690           | 3.391E+06                                                 | 2.893E+07                                                  | 5.882E+07                                                  | 6.773E+07                                                  | 9.358E+07                                                  |
| 150                                    | 3.8100  | 1.02828           | 1.729E+06                                                 | 1.474E+07                                                  | 2.998E+07                                                  | 3.452E+07                                                  | 4.770E+07                                                  |
| 200                                    | 5.0800  | 1.37104           | 5.271E+05                                                 | 4.496E+06                                                  | 9.143E+06                                                  | 1.053E+07                                                  | 1.454E+07                                                  |
| 250                                    | 6.3500  | 1.71380           | 2.004E+05                                                 | 1.709E+06                                                  | 3.476E+06                                                  | 4.002E+06                                                  | 5.529E+06                                                  |
| 300                                    | 7.6200  | 2.05656           | 9.225E+04                                                 | 7.868E+05                                                  | 1.600E+06                                                  | 1.842E+06                                                  | 2.545E+06                                                  |
| 350                                    | 8.8900  | 2.39932           | 5.039E+04                                                 | 4.298E+05                                                  | 8.740E+05                                                  | 1.006E+06                                                  | 1.390E+06                                                  |
| 400                                    | 10.1600 | 2.74208           | 3.093E+04                                                 | 2.638E+05                                                  | 5.365E+05                                                  | 6.177E+05                                                  | 8.534E+05                                                  |
| 500                                    | 12.7000 | 3.42760           | 1.349E+04                                                 | 1.150E+05                                                  | 2.340E+05                                                  | 2.694E+05                                                  | 3.722E+05                                                  |
| 600                                    | 15.2400 | 4.11312           | 6.085E+03                                                 | 5.190E+04                                                  | 1.055E+05                                                  | 1.215E+05                                                  | 1.679E+05                                                  |
| 700                                    | 17.7800 | 4.79864           | 2.833E+03                                                 | 2.417E+04                                                  | 4.914E+04                                                  | 5.658E+04                                                  | 7.818E+04                                                  |
| 800                                    | 20.3200 | 5.48416           | 1.515E+03                                                 | 1.293E+04                                                  | 2.629E+04                                                  | 3.026E+04                                                  | 4.182E+04                                                  |
| 900                                    | 22.8600 | 6.16969           | 9.496E+02                                                 | 8.100E+03                                                  | 1.647E+04                                                  | 1.896E+04                                                  | 2.620E+04                                                  |
| 1000                                   | 25.4000 | 6.85521           | 6.821E+02                                                 | 5.819E+03                                                  | 1.183E+04                                                  | 1.362E+04                                                  | 1.882E+04                                                  |





# GTO-Displacement Damage GaAs from Van Allen Belts

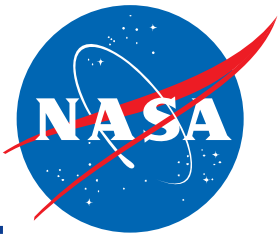
NIEL Equivalent Fluences in Gallium Arsenide for Phase 1 (Conf. Level 95%)

| Aluminum Solid-Sphere Shield Thickness |         |                   | 1 MeV Equivalent Proton Fluence | 10 MeV Equivalent Proton Fluence | 50 MeV Equivalent Proton Fluence | 63 MeV Equivalent Proton Fluence | 1 MeV Equivalent Neutron Fluence |
|----------------------------------------|---------|-------------------|---------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| mils                                   | mm      | g/cm <sup>2</sup> | #/cm <sup>2</sup> per Rev       | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        |
| 1                                      | 0.0254  | 0.00686           | 9.731E+10                       | 7.974E+11                        | 1.401E+12                        | 1.430E+12                        | 5.722E+12                        |
| 3                                      | 0.0762  | 0.02057           | 6.132E+09                       | 5.025E+10                        | 8.830E+10                        | 9.013E+10                        | 3.605E+11                        |
| 10                                     | 0.2540  | 0.06855           | 4.244E+08                       | 3.477E+09                        | 6.111E+09                        | 6.237E+09                        | 2.495E+10                        |
| 25                                     | 0.6350  | 0.17138           | 1.211E+08                       | 9.922E+08                        | 1.744E+09                        | 1.780E+09                        | 7.119E+09                        |
| 50                                     | 1.2700  | 0.34276           | 5.554E+07                       | 4.551E+08                        | 7.998E+08                        | 8.164E+08                        | 3.266E+09                        |
| 60                                     | 1.5240  | 0.41131           | 4.244E+07                       | 3.477E+08                        | 6.111E+08                        | 6.237E+08                        | 2.495E+09                        |
| 75                                     | 1.9050  | 0.51414           | 2.888E+07                       | 2.367E+08                        | 4.159E+08                        | 4.245E+08                        | 1.698E+09                        |
| 100                                    | 2.5400  | 0.68552           | 1.513E+07                       | 1.240E+08                        | 2.179E+08                        | 2.224E+08                        | 8.896E+08                        |
| 125                                    | 3.1750  | 0.85690           | 8.487E+06                       | 6.955E+07                        | 1.222E+08                        | 1.247E+08                        | 4.990E+08                        |
| 150                                    | 3.8100  | 1.02828           | 5.177E+06                       | 4.242E+07                        | 7.455E+07                        | 7.609E+07                        | 3.044E+08                        |
| 200                                    | 5.0800  | 1.37104           | 2.488E+06                       | 2.039E+07                        | 3.583E+07                        | 3.657E+07                        | 1.463E+08                        |
| 250                                    | 6.3500  | 1.71380           | 1.549E+06                       | 1.269E+07                        | 2.230E+07                        | 2.276E+07                        | 9.105E+07                        |
| 300                                    | 7.6200  | 2.05656           | 1.169E+06                       | 9.576E+06                        | 1.683E+07                        | 1.718E+07                        | 6.871E+07                        |
| 350                                    | 8.8900  | 2.39932           | 9.620E+05                       | 7.883E+06                        | 1.385E+07                        | 1.414E+07                        | 5.656E+07                        |
| 400                                    | 10.1600 | 2.74208           | 8.509E+05                       | 6.973E+06                        | 1.225E+07                        | 1.251E+07                        | 5.003E+07                        |
| 500                                    | 12.7000 | 3.42760           | 7.043E+05                       | 5.771E+06                        | 1.014E+07                        | 1.035E+07                        | 4.141E+07                        |
| 600                                    | 15.2400 | 4.11312           | 6.132E+05                       | 5.025E+06                        | 8.830E+06                        | 9.013E+06                        | 3.605E+07                        |
| 700                                    | 17.7800 | 4.79864           | 5.421E+05                       | 4.442E+06                        | 7.807E+06                        | 7.968E+06                        | 3.187E+07                        |
| 800                                    | 20.3200 | 5.48416           | 4.799E+05                       | 3.932E+06                        | 6.911E+06                        | 7.054E+06                        | 2.822E+07                        |
| 900                                    | 22.8600 | 6.16969           | 4.421E+05                       | 3.623E+06                        | 6.367E+06                        | 6.498E+06                        | 2.600E+07                        |
| 1000                                   | 25.4000 | 6.85521           | 4.110E+05                       | 3.368E+06                        | 5.919E+06                        | 6.041E+06                        | 2.417E+07                        |

NIEL Equivalent Fluences in Gallium Arsenide for Phase 2 (Conf. Level 95%)

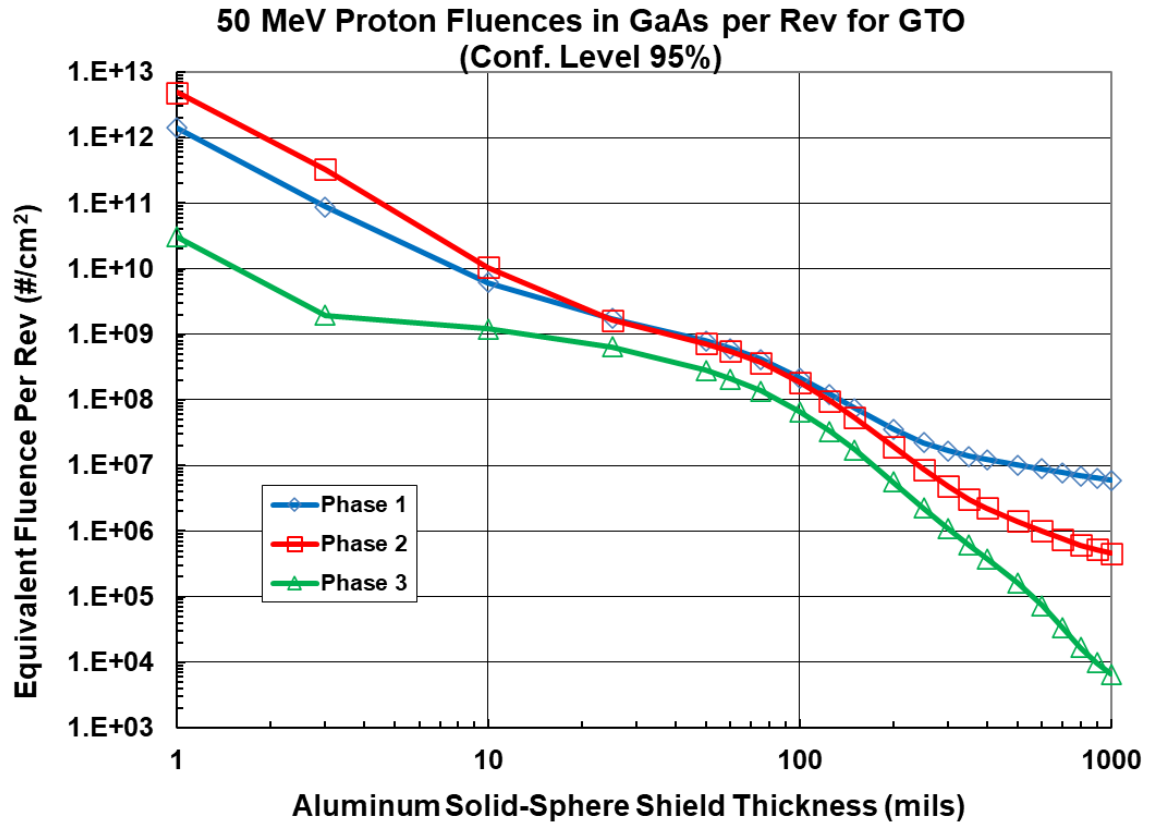
| Aluminum Solid-Sphere Shield Thickness |         |                   | 1 MeV Equivalent Proton Fluence | 10 MeV Equivalent Proton Fluence | 50 MeV Equivalent Proton Fluence | 63 MeV Equivalent Proton Fluence | 1 MeV Equivalent Neutron Fluence |
|----------------------------------------|---------|-------------------|---------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| mils                                   | mm      | g/cm <sup>2</sup> | #/cm <sup>2</sup> per Rev       | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        |
| 1                                      | 0.0254  | 0.00686           | 3.352E+11                       | 2.747E+12                        | 4.827E+12                        | 4.927E+12                        | 1.971E+13                        |
| 3                                      | 0.0762  | 0.02057           | 2.273E+10                       | 1.863E+11                        | 3.273E+11                        | 3.341E+11                        | 1.336E+12                        |
| 10                                     | 0.2540  | 0.06855           | 7.351E+08                       | 6.024E+09                        | 1.059E+10                        | 1.080E+10                        | 4.322E+10                        |
| 25                                     | 0.6350  | 0.17138           | 1.147E+08                       | 9.397E+08                        | 1.651E+09                        | 1.686E+09                        | 6.743E+09                        |
| 50                                     | 1.2700  | 0.34276           | 5.058E+07                       | 4.144E+08                        | 7.283E+08                        | 7.434E+08                        | 2.974E+09                        |
| 60                                     | 1.5240  | 0.41131           | 3.823E+07                       | 3.132E+08                        | 5.505E+08                        | 5.619E+08                        | 2.248E+09                        |
| 75                                     | 1.9050  | 0.51414           | 2.547E+07                       | 2.087E+08                        | 3.667E+08                        | 3.743E+08                        | 1.497E+09                        |
| 100                                    | 2.5400  | 0.68552           | 1.291E+07                       | 1.058E+08                        | 1.859E+08                        | 1.897E+08                        | 7.590E+08                        |
| 125                                    | 3.1750  | 0.85690           | 6.734E+06                       | 5.518E+07                        | 9.697E+07                        | 9.897E+07                        | 3.959E+08                        |
| 150                                    | 3.8100  | 1.02828           | 3.735E+06                       | 3.060E+07                        | 5.378E+07                        | 5.489E+07                        | 2.196E+08                        |
| 200                                    | 5.0800  | 1.37104           | 1.361E+06                       | 1.116E+07                        | 1.961E+07                        | 2.001E+07                        | 8.005E+07                        |
| 250                                    | 6.3500  | 1.71380           | 6.087E+05                       | 4.988E+06                        | 8.765E+06                        | 8.947E+06                        | 3.579E+07                        |
| 300                                    | 7.6200  | 2.05656           | 3.323E+05                       | 2.723E+06                        | 4.785E+06                        | 4.884E+06                        | 1.954E+07                        |
| 350                                    | 8.8900  | 2.39932           | 2.117E+05                       | 1.735E+06                        | 3.049E+06                        | 3.112E+06                        | 1.245E+07                        |
| 400                                    | 10.1600 | 2.74208           | 1.553E+05                       | 1.272E+06                        | 2.236E+06                        | 2.282E+06                        | 9.128E+06                        |
| 500                                    | 12.7000 | 3.42760           | 9.763E+04                       | 8.000E+05                        | 1.406E+06                        | 1.435E+06                        | 5.740E+06                        |
| 600                                    | 15.2400 | 4.11312           | 6.940E+04                       | 5.687E+05                        | 9.993E+05                        | 1.020E+06                        | 4.080E+06                        |
| 700                                    | 17.7800 | 4.79864           | 5.264E+04                       | 4.313E+05                        | 7.580E+05                        | 7.736E+05                        | 3.095E+06                        |
| 800                                    | 20.3200 | 5.48416           | 4.205E+04                       | 3.446E+05                        | 6.055E+05                        | 6.180E+05                        | 2.472E+06                        |
| 900                                    | 22.8600 | 6.16969           | 3.617E+04                       | 2.964E+05                        | 5.208E+05                        | 5.316E+05                        | 2.127E+06                        |
| 1000                                   | 25.4000 | 6.85521           | 3.176E+04                       | 2.602E+05                        | 4.573E+05                        | 4.668E+05                        | 1.867E+06                        |

# GTO-Displacement Damage GaAs from Van Allen Belts

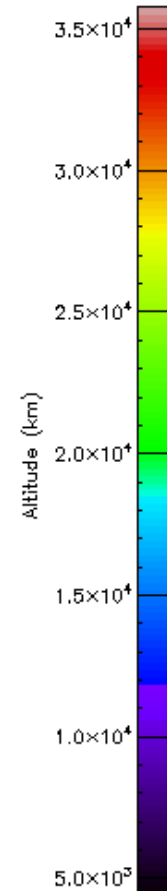
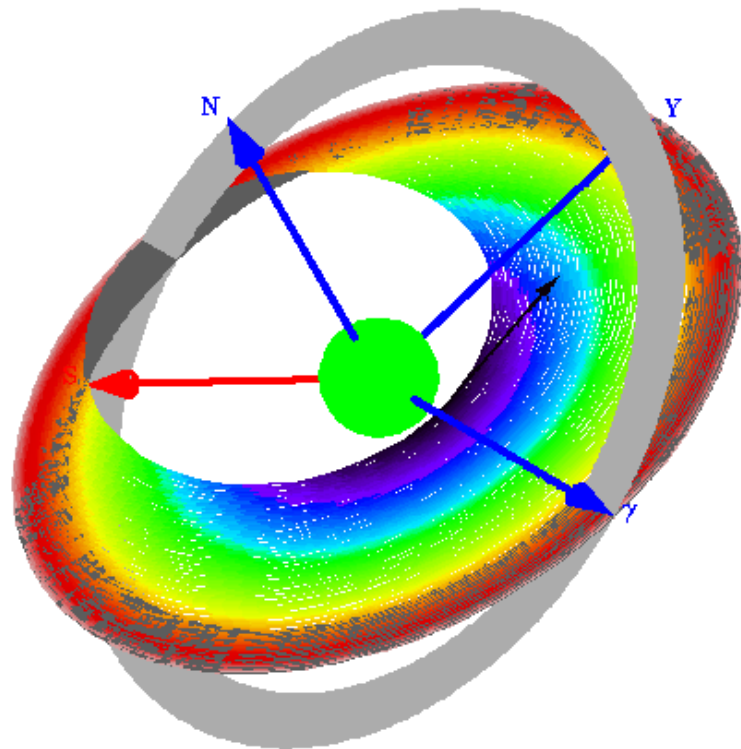
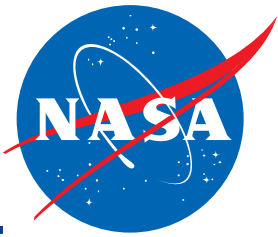


NIEL Equivalent Fluences in Gallium Arsenide for Phase 3 (Conf. Level 95%)

| Aluminum Solid-Sphere Shield Thickness |         |                   | 1 MeV Equivalent Proton Fluence | 10 MeV Equivalent Proton Fluence | 50 MeV Equivalent Proton Fluence | 63 MeV Equivalent Proton Fluence | 1 MeV Equivalent Neutron Fluence |
|----------------------------------------|---------|-------------------|---------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| mils                                   | mm      | g/cm <sup>2</sup> | #/cm <sup>2</sup> per Rev       | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        | #/cm <sup>2</sup> per Rev        |
| 1                                      | 0.0254  | 0.00686           | 2.121E+09                       | 1.738E+10                        | 3.054E+10                        | 3.117E+10                        | 1.247E+11                        |
| 3                                      | 0.0762  | 0.02057           | 1.367E+08                       | 1.120E+09                        | 1.969E+09                        | 2.009E+09                        | 8.037E+09                        |
| 10                                     | 0.2540  | 0.06855           | 8.405E+07                       | 6.887E+08                        | 1.210E+09                        | 1.235E+09                        | 4.942E+09                        |
| 25                                     | 0.6350  | 0.17138           | 4.430E+07                       | 3.630E+08                        | 6.379E+08                        | 6.510E+08                        | 2.604E+09                        |
| 50                                     | 1.2700  | 0.34276           | 1.952E+07                       | 1.599E+08                        | 2.810E+08                        | 2.868E+08                        | 1.147E+09                        |
| 60                                     | 1.5240  | 0.41131           | 1.449E+07                       | 1.187E+08                        | 2.087E+08                        | 2.130E+08                        | 8.520E+08                        |
| 75                                     | 1.9050  | 0.51414           | 9.419E+06                       | 7.718E+07                        | 1.356E+08                        | 1.384E+08                        | 5.538E+08                        |
| 100                                    | 2.5400  | 0.68552           | 4.608E+06                       | 3.776E+07                        | 6.636E+07                        | 6.773E+07                        | 2.709E+08                        |
| 125                                    | 3.1750  | 0.85690           | 2.299E+06                       | 1.884E+07                        | 3.311E+07                        | 3.379E+07                        | 1.352E+08                        |
| 150                                    | 3.8100  | 1.02828           | 1.203E+06                       | 9.856E+06                        | 1.732E+07                        | 1.768E+07                        | 7.072E+07                        |
| 200                                    | 5.0800  | 1.37104           | 3.893E+05                       | 3.190E+06                        | 5.606E+06                        | 5.722E+06                        | 2.289E+07                        |
| 250                                    | 6.3500  | 1.71380           | 1.551E+05                       | 1.271E+06                        | 2.233E+06                        | 2.279E+06                        | 9.117E+06                        |
| 300                                    | 7.6200  | 2.05656           | 7.487E+04                       | 6.135E+05                        | 1.078E+06                        | 1.100E+06                        | 4.402E+06                        |
| 350                                    | 8.8900  | 2.39932           | 4.207E+04                       | 3.448E+05                        | 6.059E+05                        | 6.184E+05                        | 2.474E+06                        |
| 400                                    | 10.1600 | 2.74208           | 2.628E+04                       | 2.153E+05                        | 3.784E+05                        | 3.862E+05                        | 1.545E+06                        |
| 500                                    | 12.7000 | 3.42760           | 1.145E+04                       | 9.381E+04                        | 1.649E+05                        | 1.683E+05                        | 6.731E+05                        |
| 600                                    | 15.2400 | 4.11312           | 5.072E+03                       | 4.156E+04                        | 7.304E+04                        | 7.455E+04                        | 2.982E+05                        |
| 700                                    | 17.7800 | 4.79864           | 2.304E+03                       | 1.888E+04                        | 3.318E+04                        | 3.387E+04                        | 1.355E+05                        |
| 800                                    | 20.3200 | 5.48416           | 1.174E+03                       | 9.618E+03                        | 1.690E+04                        | 1.725E+04                        | 6.901E+04                        |
| 900                                    | 22.8600 | 6.16969           | 6.859E+02                       | 5.621E+03                        | 9.877E+03                        | 1.008E+04                        | 4.033E+04                        |
| 1000                                   | 25.4000 | 6.85521           | 4.545E+02                       | 3.725E+03                        | 6.545E+03                        | 6.681E+03                        | 2.672E+04                        |



# Spiral Trajectory



Time in the Van Allen Belts:

- 2 months
- 4 months
- 6 months
- 8 months
- 10 months

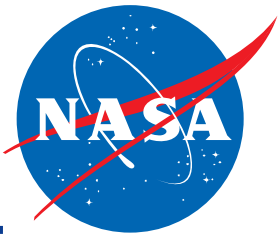
Trapped Protons: AP-9

Trapped Electrons: AE-9

Solar Protons: Not included

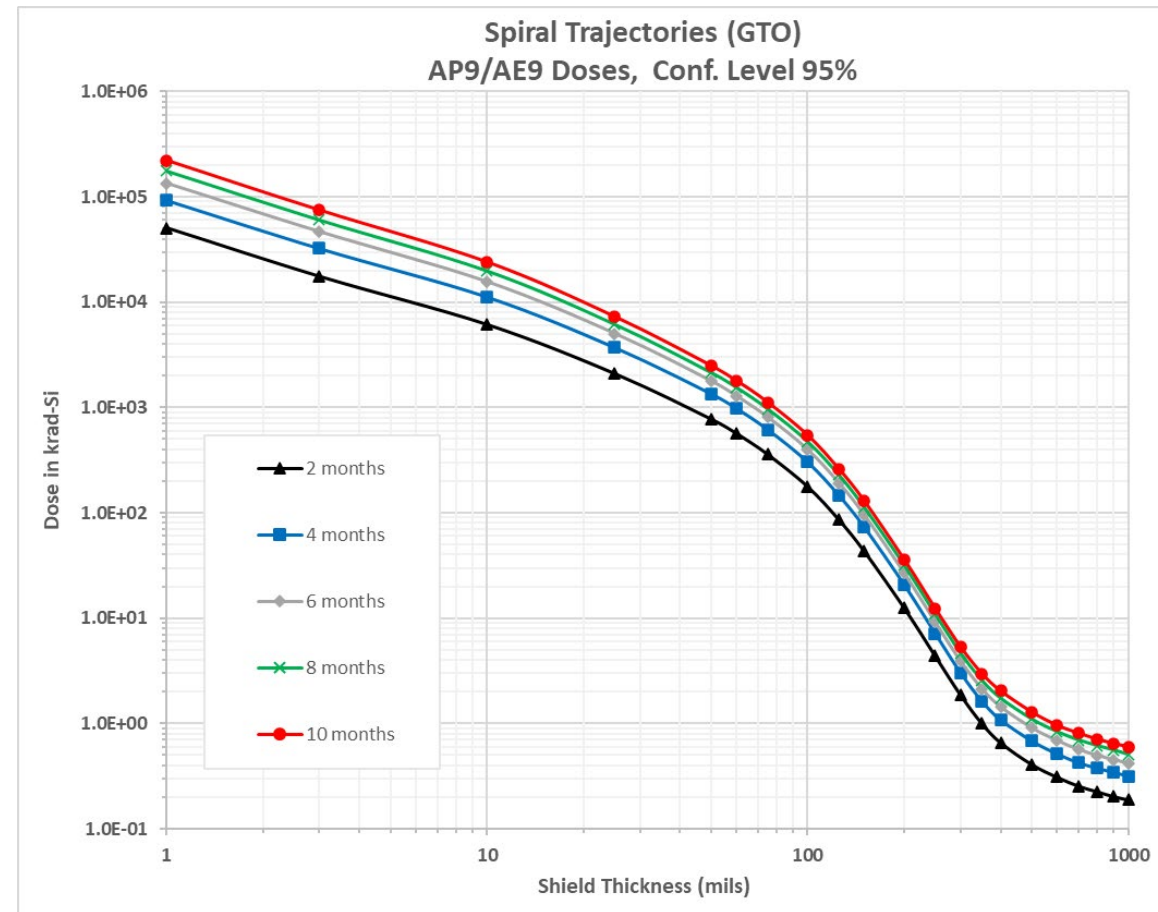
Transport Model: Novice, adjoint solid sphere aluminum, Si target

# Spiral Trajectory TID for Different Durations



| AP9/AE9 Total Dose (Conf. Level 95%) |                                  |                                  |                                  |                                  |                                   |
|--------------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|-----------------------------------|
| Shield Thickness<br>(mils)           | 2-Month<br>GTO Dose<br>(krad-Si) | 4-Month<br>GTO Dose<br>(krad-Si) | 6-Month<br>GTO Dose<br>(krad-Si) | 8-Month<br>GTO Dose<br>(krad-Si) | 10-Month<br>GTO Dose<br>(krad-Si) |
| 1                                    | 5.05E+04                         | 9.26E+04                         | 1.34E+05                         | 1.77E+05                         | 2.21E+05                          |
| 3                                    | 1.75E+04                         | 3.23E+04                         | 4.65E+04                         | 6.06E+04                         | 7.46E+04                          |
| 10                                   | 6.11E+03                         | 1.12E+04                         | 1.56E+04                         | 1.99E+04                         | 2.40E+04                          |
| 25                                   | 2.09E+03                         | 3.71E+03                         | 5.03E+03                         | 6.18E+03                         | 7.28E+03                          |
| 50                                   | 7.74E+02                         | 1.35E+03                         | 1.78E+03                         | 2.15E+03                         | 2.49E+03                          |
| 60                                   | 5.65E+02                         | 9.79E+02                         | 1.28E+03                         | 1.55E+03                         | 1.79E+03                          |
| 75                                   | 3.58E+02                         | 6.18E+02                         | 8.08E+02                         | 9.72E+02                         | 1.12E+03                          |
| 100                                  | 1.77E+02                         | 3.04E+02                         | 3.97E+02                         | 4.75E+02                         | 5.45E+02                          |
| 125                                  | 8.61E+01                         | 1.47E+02                         | 1.92E+02                         | 2.29E+02                         | 2.62E+02                          |
| 150                                  | 4.32E+01                         | 7.34E+01                         | 9.53E+01                         | 1.13E+02                         | 1.30E+02                          |
| 200                                  | 1.25E+01                         | 2.08E+01                         | 2.67E+01                         | 3.17E+01                         | 3.61E+01                          |
| 250                                  | 4.38E+00                         | 7.17E+00                         | 9.15E+00                         | 1.09E+01                         | 1.24E+01                          |
| 300                                  | 1.86E+00                         | 3.02E+00                         | 3.88E+00                         | 4.64E+00                         | 5.34E+00                          |
| 350                                  | 9.96E-01                         | 1.62E+00                         | 2.12E+00                         | 2.55E+00                         | 2.97E+00                          |
| 400                                  | 6.58E-01                         | 1.08E+00                         | 1.43E+00                         | 1.73E+00                         | 2.04E+00                          |
| 500                                  | 4.10E-01                         | 6.83E-01                         | 9.07E-01                         | 1.10E+00                         | 1.29E+00                          |
| 600                                  | 3.10E-01                         | 5.13E-01                         | 6.84E-01                         | 8.32E-01                         | 9.63E-01                          |
| 700                                  | 2.55E-01                         | 4.23E-01                         | 5.65E-01                         | 6.94E-01                         | 8.13E-01                          |
| 800                                  | 2.26E-01                         | 3.76E-01                         | 4.96E-01                         | 6.14E-01                         | 7.12E-01                          |
| 900                                  | 2.03E-01                         | 3.43E-01                         | 4.51E-01                         | 5.58E-01                         | 6.48E-01                          |
| 1000                                 | 1.89E-01                         | 3.17E-01                         | 4.19E-01                         | 5.06E-01                         | 6.03E-01                          |

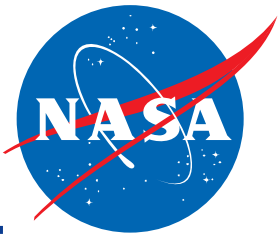
Dose is dominated by trapped electrons



Additional shielding useful in reducing the dose to meet requirements

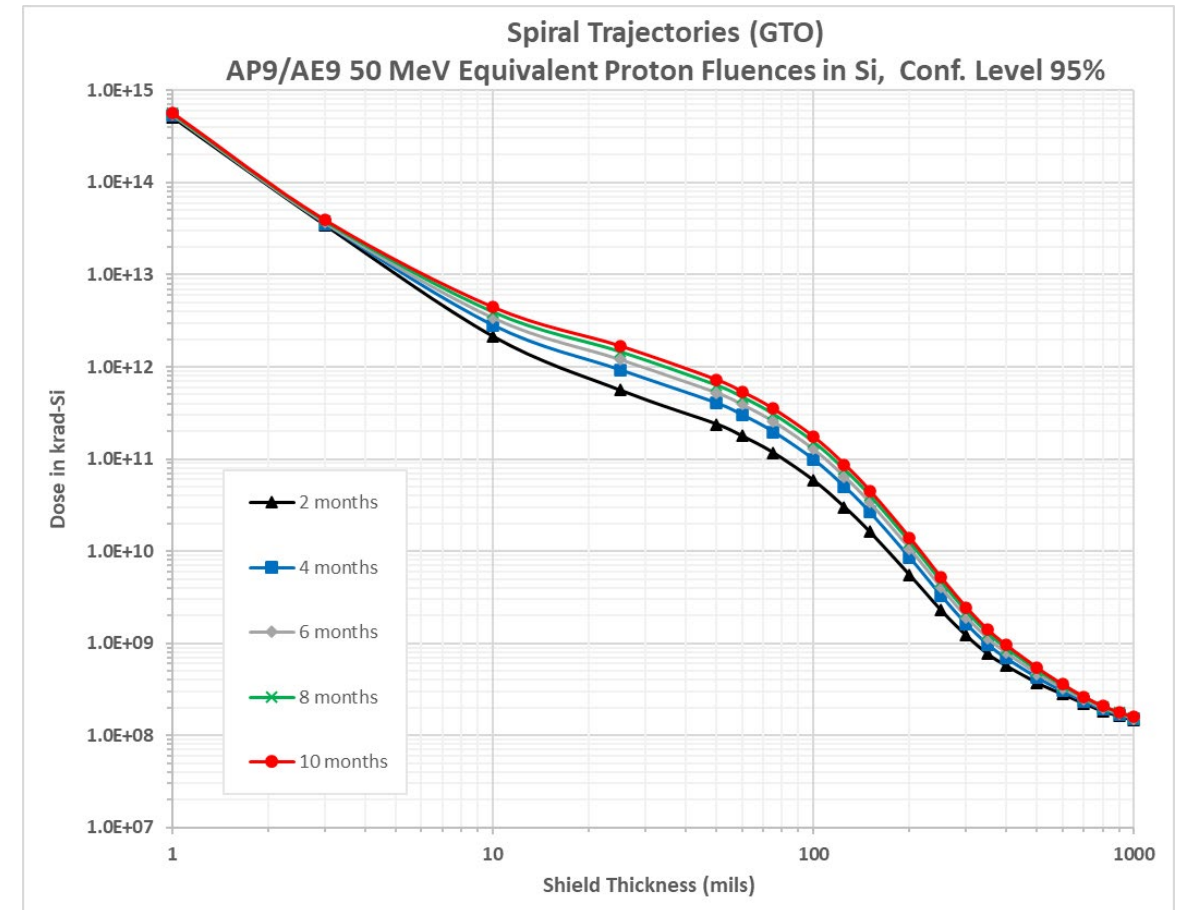
Ray trace calculations can help improve the dose results for requirements by taking advantage spacecraft geometry

# Spiral Trajectory 50 MeV Equivalent Proton Fluence Si

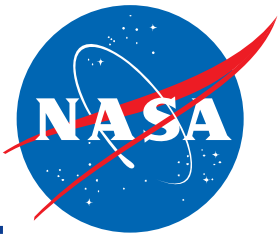


NIEL Equivalent Fluences in Silicon (Conf. Level 95%)

| Shield Thickness | 2-Month GTO Dose                       | 4-Month GTO Dose                       | 6-Month GTO Dose                       | 8-Month GTO Dose                       | 10-Month GTO Dose                      |
|------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| mils             | 50 MeV Equivalent Proton Fluence #/cm2 | 50 MeV Equivalent Proton Fluence #/cm2 | 50 MeV Equivalent Proton Fluence #/cm2 | 50 MeV Equivalent Proton Fluence #/cm2 | 50 MeV Equivalent Proton Fluence #/cm2 |
| 1                | 5.10E+14                               | 5.39E+14                               | 5.52E+14                               | 5.62E+14                               | 5.70E+14                               |
| 3                | 3.43E+13                               | 3.58E+13                               | 3.69E+13                               | 3.81E+13                               | 3.89E+13                               |
| 10               | 2.14E+12                               | 2.84E+12                               | 3.43E+12                               | 3.94E+12                               | 4.43E+12                               |
| 25               | 5.57E+11                               | 9.25E+11                               | 1.21E+12                               | 1.46E+12                               | 1.68E+12                               |
| 50               | 2.39E+11                               | 4.05E+11                               | 5.26E+11                               | 6.29E+11                               | 7.22E+11                               |
| 60               | 1.78E+11                               | 3.02E+11                               | 3.92E+11                               | 4.69E+11                               | 5.36E+11                               |
| 75               | 1.17E+11                               | 1.98E+11                               | 2.56E+11                               | 3.07E+11                               | 3.51E+11                               |
| 100              | 5.90E+10                               | 9.95E+10                               | 1.29E+11                               | 1.53E+11                               | 1.75E+11                               |
| 125              | 3.02E+10                               | 5.03E+10                               | 6.47E+10                               | 7.65E+10                               | 8.74E+10                               |
| 150              | 1.62E+10                               | 2.65E+10                               | 3.38E+10                               | 3.99E+10                               | 4.54E+10                               |
| 200              | 5.49E+09                               | 8.48E+09                               | 1.06E+10                               | 1.24E+10                               | 1.39E+10                               |
| 250              | 2.30E+09                               | 3.32E+09                               | 4.05E+09                               | 4.66E+09                               | 5.23E+09                               |
| 300              | 1.22E+09                               | 1.63E+09                               | 1.93E+09                               | 2.20E+09                               | 2.45E+09                               |
| 350              | 7.71E+08                               | 9.74E+08                               | 1.13E+09                               | 1.28E+09                               | 1.41E+09                               |
| 400              | 5.72E+08                               | 6.91E+08                               | 7.89E+08                               | 8.76E+08                               | 9.59E+08                               |
| 500              | 3.74E+08                               | 4.25E+08                               | 4.66E+08                               | 5.05E+08                               | 5.41E+08                               |
| 600              | 2.81E+08                               | 3.04E+08                               | 3.25E+08                               | 3.43E+08                               | 3.58E+08                               |
| 700              | 2.23E+08                               | 2.36E+08                               | 2.46E+08                               | 2.55E+08                               | 2.63E+08                               |
| 800              | 1.85E+08                               | 1.92E+08                               | 1.98E+08                               | 2.04E+08                               | 2.09E+08                               |
| 900              | 1.63E+08                               | 1.69E+08                               | 1.73E+08                               | 1.76E+08                               | 1.80E+08                               |
| 1000             | 1.47E+08                               | 1.51E+08                               | 1.53E+08                               | 1.56E+08                               | 1.59E+08                               |

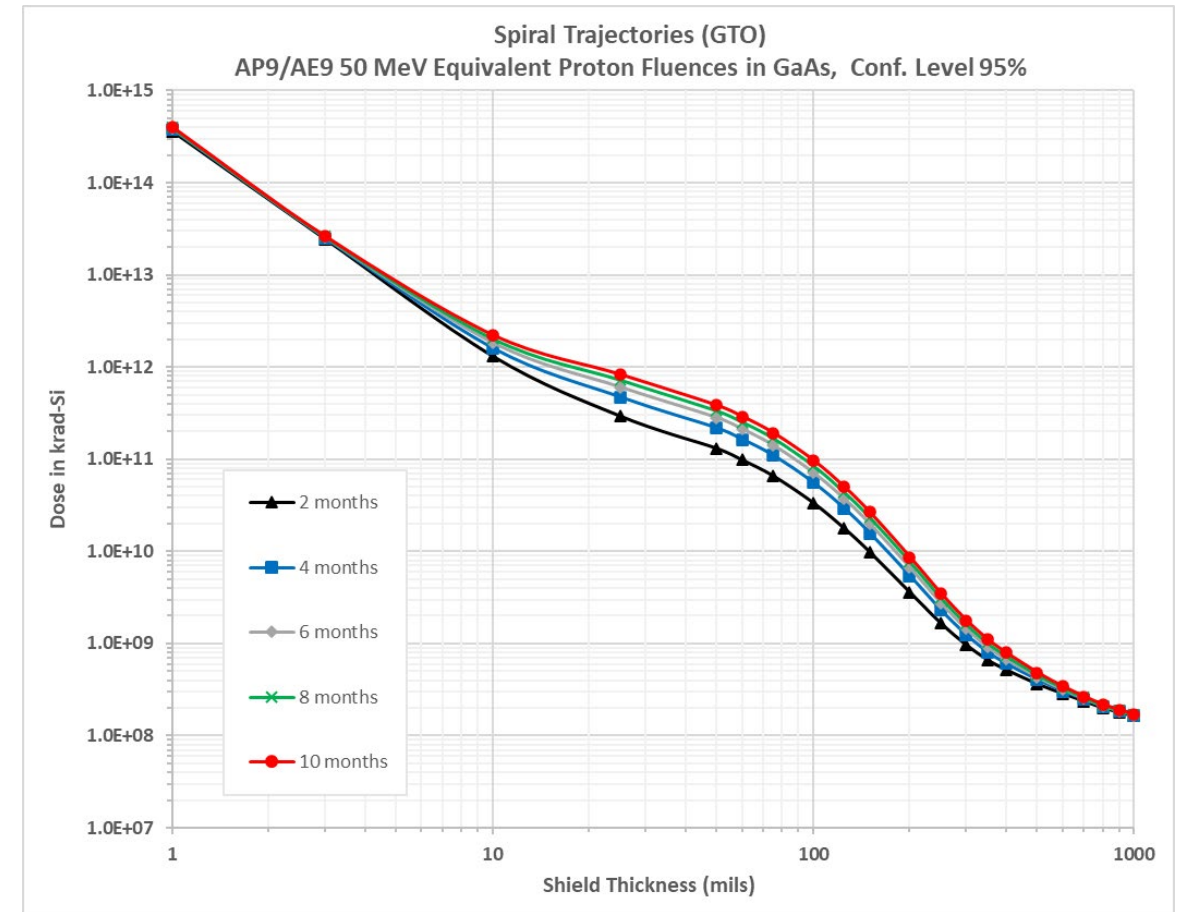


# Spiral Trajectory 50 MeV Equivalent Proton Fluence GaAs



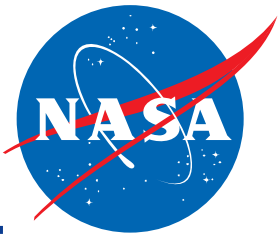
NIEL Equivalent Fluences in GaAs (Conf. Level 95%)

| Shield Thickness | 2-Month GTO Dose                       | 4-Month GTO Dose                       | 6-Month GTO Dose                       | 8-Month GTO Dose                       | 10-Month GTO Dose                      |
|------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| mils             | 50 MeV Equivalent Proton Fluence #/cm2 | 50 MeV Equivalent Proton Fluence #/cm2 | 50 MeV Equivalent Proton Fluence #/cm2 | 50 MeV Equivalent Proton Fluence #/cm2 | 50 MeV Equivalent Proton Fluence #/cm2 |
| 1                | 3.63E+14                               | 3.84E+14                               | 3.92E+14                               | 3.97E+14                               | 4.05E+14                               |
| 3                | 2.45E+13                               | 2.52E+13                               | 2.57E+13                               | 2.61E+13                               | 2.64E+13                               |
| 10               | 1.31E+12                               | 1.61E+12                               | 1.84E+12                               | 2.04E+12                               | 2.23E+12                               |
| 25               | 2.93E+11                               | 4.72E+11                               | 6.05E+11                               | 7.25E+11                               | 8.29E+11                               |
| 50               | 1.31E+11                               | 2.18E+11                               | 2.83E+11                               | 3.36E+11                               | 3.84E+11                               |
| 60               | 9.81E+10                               | 1.64E+11                               | 2.13E+11                               | 2.54E+11                               | 2.91E+11                               |
| 75               | 6.59E+10                               | 1.10E+11                               | 1.42E+11                               | 1.69E+11                               | 1.93E+11                               |
| 100              | 3.36E+10                               | 5.57E+10                               | 7.17E+10                               | 8.53E+10                               | 9.73E+10                               |
| 125              | 1.77E+10                               | 2.91E+10                               | 3.71E+10                               | 4.37E+10                               | 4.99E+10                               |
| 150              | 9.84E+09                               | 1.57E+10                               | 1.99E+10                               | 2.34E+10                               | 2.65E+10                               |
| 200              | 3.60E+09                               | 5.41E+09                               | 6.67E+09                               | 7.73E+09                               | 8.67E+09                               |
| 250              | 1.66E+09                               | 2.30E+09                               | 2.75E+09                               | 3.15E+09                               | 3.49E+09                               |
| 300              | 9.68E+08                               | 1.24E+09                               | 1.44E+09                               | 1.62E+09                               | 1.78E+09                               |
| 350              | 6.64E+08                               | 8.03E+08                               | 9.12E+08                               | 1.01E+09                               | 1.10E+09                               |
| 400              | 5.20E+08                               | 6.03E+08                               | 6.72E+08                               | 7.33E+08                               | 7.92E+08                               |
| 500              | 3.65E+08                               | 4.03E+08                               | 4.32E+08                               | 4.59E+08                               | 4.83E+08                               |
| 600              | 2.88E+08                               | 3.04E+08                               | 3.17E+08                               | 3.31E+08                               | 3.41E+08                               |
| 700              | 2.38E+08                               | 2.46E+08                               | 2.53E+08                               | 2.59E+08                               | 2.65E+08                               |
| 800              | 2.01E+08                               | 2.06E+08                               | 2.10E+08                               | 2.14E+08                               | 2.17E+08                               |
| 900              | 1.81E+08                               | 1.84E+08                               | 1.86E+08                               | 1.89E+08                               | 1.91E+08                               |
| 1000             | 1.63E+08                               | 1.66E+08                               | 1.67E+08                               | 1.69E+08                               | 1.70E+08                               |



# Summary

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Radiation environment changes as spacecraft move from Earth to the Moon

- Trajectory is extremely important in determining Van Allen Belt radiation environment
- TID and DDD are cumulative quantities
  - Values depend on the amount of time spent in the Van Allen Belts
  - Direct transfer lowest TID behind 100mils of aluminum 0.56 krad(Si)
  - Spiral trajectory TID ranges from 177 to 545 krad(Si) behind 100mils of aluminum for 2 months in the Van Allen Belts and 10 months in the Van Allen Belts

Amount of time in the belts will influence part selection, amount of additional radiation shielding, and need for ray-trace.

Start of science mission phase will not start at zero TID/DDD after transit through the belts. Will have to factor in mission life analysis.