NASA

Timepix Utilization

On the International Space Station

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Space Radiation Analysis Group **NASA**

Introduction

NASA utilizes Timepix pixel detector read-out chips for particle imaging and detection in various configurations for the International Space Station (ISS) and exploration-class missions.

Here we will only focus on ISS-based detectors, namely, the Radiation Environment Monitors (REMs) have been operating on ISS as Technology Demonstrations since October 2012.

REM Science Team

The number of people working the REM project has grown since 2012 and mostly consists of people affiliated with NASA Johnson Space Center and the University of Houston:

- T. Campbell-Rickets, D. Fry, R. Gaza, S. George, M. Kroupa, M. Leitab, L. Pinsky, R. Rios, E. Semones, N. Stoffle, M. Vandewalle, S. Wheeler

Additional people that support(ed) the REM science team include:

- A. Bahadori, S. Hoang, J. Idarraga, D. Turecek

Timepix Technology (A Reminder)

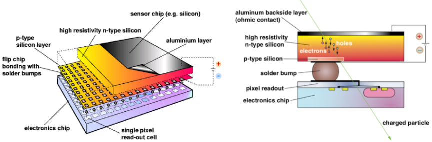


Figure 1: Medipix2 chip and Timepix assembly. (Source: CERN/Medipix.)

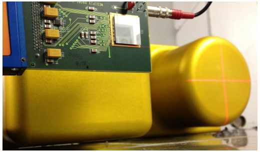


Figure 2: Timepix on carrier board in front of ISS-RAD during p^+ testing in 2014.

- Hybrid silicon pixel detector utilizing Medipix2/Timepix technology from CERN (medipix.cern.ch).
  - 256×256 pixels, each with a 55µm pitch (1.982cm^2).
  - Opening angle: 4π.
- Low mass/power/cost make it an ideal technology for space applications.

REM (Radiation Environment Monitor)

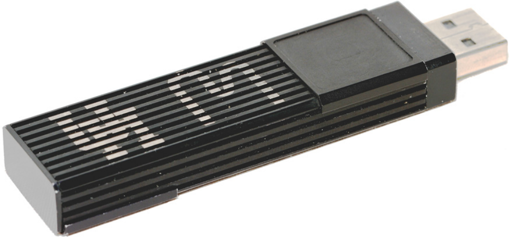


Figure 3: Radiation Environment Monitor.

- Modified IEAP[1] Timepix Lite Units.
  - 9 delivered to ISS since 2012.
    - 5 in the initial batch [1, 2].
  - 300 (500) µm thick.
  - $E_{\Delta,pixel}$ range[2]: 5 - 800 keV.
- IEAP no longer produces Timepix Lite units.
  - We are currently certifying REM2 (MiniPIX), developed by Advacam, as replacements; see R. Gaza's talk.

[1] Institute of Experimental and Applied Physics Czech Technical University.
[2] 0.005 - 2 MeV per pixel with advanced calibration.

MPT (Miniaturized Particle Telescope)

Figure 4: Miniaturized Particle Telescope. (Source: Advacam.)

- Two-layer stack of Timepix sensors developed in cooperation with Advacam.
  - 1 delivered to ISS in 2016.
  - 2× 500 µm thick.
    - Layers are 1.5cm apart.
  - $E_{\Delta,pixel}$ range: 0.005 - 2 MeV.

Data Acquisition Ops

- Data acquired on each Station Support Computer (SSC) using PixelmanISS (flight software).
  - Nominally measure raw frames with Time-over-Threshold and shutter times that vary between 0.1s and 4s (depending on pixel occupancy trending).
- Crew/ground interactions, Windows updates/reboots on the SSC decrease REM uptime.
  - Flight software updates were deployed mid-March 2018 and enabled data acquisition in the background.

Data Transfer Ops

- Data are transferred from each SSC to a network share on LS1 (Linux Server) and zipped.
- Zipped data are downlinked three times a day by Plug-in Port Utilization Officer (PLUTO) and stored in a network server run by Orbital Communications Adapter Officer (OCA).
- `cron` jobs synchronize data to SRAG's network servers and transfer to SRAG's cluster and the University of Houston for processing.

Data Processing Ops

- Additional `cron` jobs run CRIS (Cluster Reconstruction and Interpretation Software) on the raw frame data, generating ROOT TTrees for observables at the frame, cluster, and pixel level.
  - CRIS data is the starting point for 99% of the analyses.
  - Because we store raw frames, we have the ability to reprocess all data with new/improved algorithms.
- Additional (automated) processing for reporting and generic visualization.

Data Analysis Ops

As expertise in the REM team increased, we version controlled and automated many data analyses.

- Doing so enabled distributable analyses, reproducibility, and easier cross-checking.
- Routine analyses were integrated with LaTeX frameworks, which were eventually automated with `cron` and integrated into an email server for automated distribution.

And even developed user-friendly analysis/visualization tools: InCA (ROOT, standalone) [3], cris_gui (ROOT+Qt, standalone), WebREM (Python+ROOT, web).

Analyses

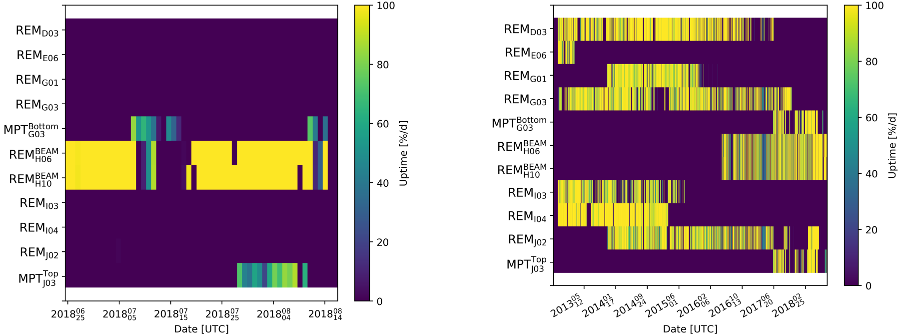
A lot of work has been performed to improve the fidelity of Timepix measurements [4].

- Better understand the sensor's characteristics.
- Extend capabilities through hardware design & development.

n(REMs) $\times$ n(locations) $\times$ n(years) $\rightsquigarrow$ large dataset.

- Ability to perform many studies with varying levels of complexity, ranging from simple trending to data unfolding and phenomenological interpretation.

REM/MPT Livetime



(a) Livetime within the past 54 days.

(b) Livetime since initial deployment.

Figure 5: Livetime per day as of 2018-08-15 for Timepix-based detectors on ISS.

Colocated Comparison

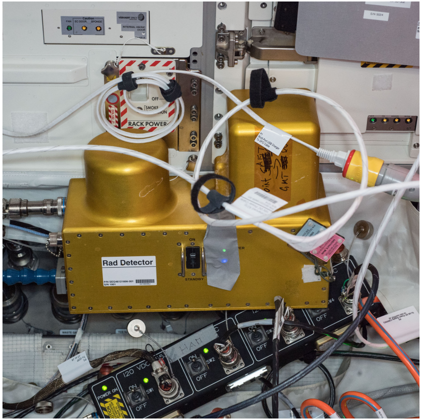


Figure 6: RAD deployment in COL1A2, oriented zenith, [2018-04-07, 2018-05-04).

- RAD located at COL1A2, oriented Zenith: [2018-04-07, 2018-05-04).
- $\mathrm{REM}^{5001}_{\mathrm{J02}}$, nearby, on SSC11.
- Livetimes greater than 93% for both instruments.
  - Significant downtime on 23 April in support of standard utility panel (SUP-1) powerdown/powerup.
    - RAD powered down for most of the day: [08:20, 19:50).

Daily Dose

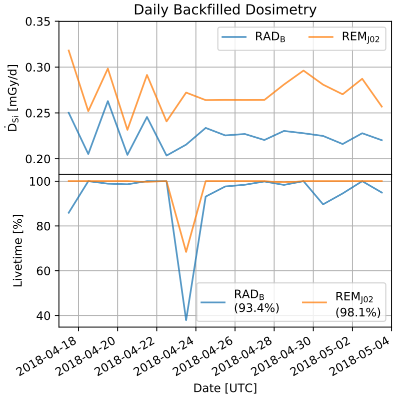


Figure 7: Daily absorbed dose rate in Silicon between [2018-04-07, 2018-05-04).

- Very similar trending with a linear offset between RAD_B and REM_{J02}^{5001}.
  - Expected given SSC movement and changes to localized shielding.
- Daily $\mu_{\dot{D}_{Si}} \pm \sigma_{\dot{D}_{Si}}$ [µGy/d]:
  - RAD_B: 225.91 ± 15.54
  - REM_{J02}^{5001}: 272.52 ± 21.23

Dose Rate

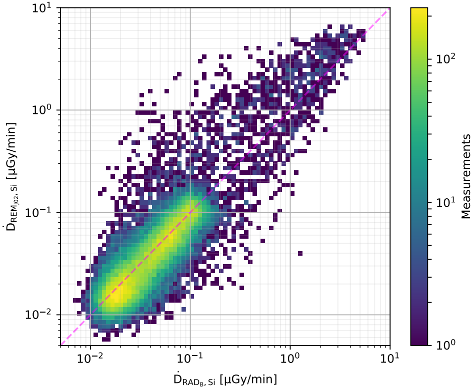


Figure 8: Absorbed dose rate in silicon as measured simultaneously between RAD_B and REM^{5001}_{J02} between [2018-04-07, 2018-05-04).

- Good correlation in dosimetry as a function time.
- Daily $\mu_{\dot{D}_{Si}} \pm \sigma_{\dot{D}_{Si}}$ [μGy/d]:
  - Galactic Cosmic Radiation (GCR):
    - RAD_B: 121.16 ± 2.08
    - REM^{5001}_{J02}: 112.71 ± 2.54
  - South Atlantic Anomaly (SAA), defined by $|B| < 23\mu T$, $L < 3$:
    - RAD_B: 104.75 ± 15.89
    - REM^{5001}_{J02}: 159.81 ± 22.74

dE/dx Spectra

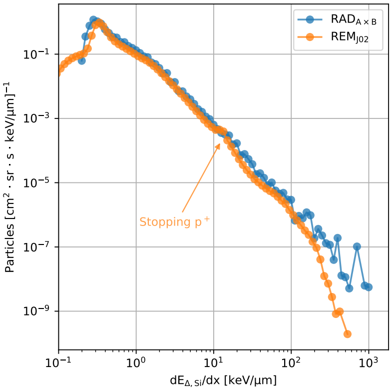


Figure 9: dE_{Si}/dx between [2018-04-07, 2018-05-04).

- Fiducial volumes for dE/dx:
  - RAD $\Omega_{A\times B} = \pi/6$
  - REM $\Omega = 4\pi$
- Substantial agreement between dE/dx spectra.
  - Shift in MIP peak due to sensor thickness; 300μm for RAD_B & 500μm for REM^{5001}_{J02}.
  - In REM^{5001}_{J02}, you can also see:
    - Stopping proton artifact around 12 keV/μm (in Si).
    - Volcano effect in high-dE/dx events (above 15 keV/μm).

Light Ion Identification (M. Kroupa et al.)

Image redacted; see publication.

Image redacted; see publication.

- Can perform Bragg curve spectroscopy on each track.
  - Enables use of single-layer Timepix as a multi-layer telescope with no material between layers, e.g., Ref [3, 5].
- The change in dE/dx can be used to identify different isotopes of light elements.
- Publication in work [6].

Parton Showers

Parton showers are not uncommon on ISS, but it's very easy to visualize in Timepix. Ongoing work by M. Kroupa on correlating showers with vehicle activity and other environmental changes.

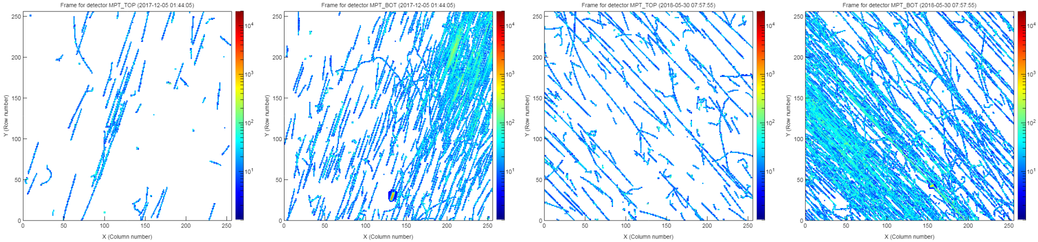


Figure 10: Showers in the top and bottom layers of the MPT.

ISS Reporting

For ISS, one of our most significant *operational* products for all detectors is post mission dosimetry reporting.

- Provides a broad overview of dosimetry from all of the available instruments (active and passive) located across ISS.
- Primary data product used in this are average daily doses rates (total cumulative dose normalized to mission duration).
  - Dosimetry from active detectors are split into Solar Particle Event (SPE), SAA, and GCR environments.
  - Absorbed dose is the only data product common to *all* of the radiation detectors within ISS.

Backfilling

One of the biggest source of downtimes was weekend outages. With the installation of Task Scheduler (for data acquisition), REM uptimes improved from $\mathcal{O}(60\%)$ to $\mathcal{O}(98\%)$.

- Another source is when REM is unplugged for another activity.

In order to generate accurate integral doses for post mission reporting, I came up with a method to "backfill" missing measurements [7, 8].

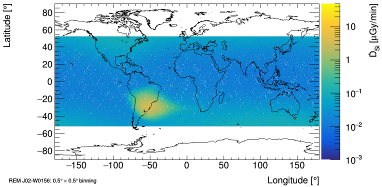
- Backfilled data is not a surrogate for real measurements, especially during an energetic solar particle event.
- Can be used on any instrument and in principle for any observable as a function of time.

Backfilling Algorithm

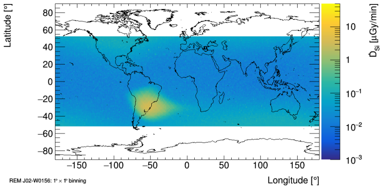
Briefly, the algorithm steps through a series of 3D and 2D histograms (of different resolutions) which contain the observable of interest, e.g. average dose rate, as a function of longitude, latitude, altitude, and time.

- Vehicle position is looked up through the use of timestamps.
- Iterate from highest resolution to lowest until non-zero value is found.
    - Typically ∼99% of the missing REM data is backfilled using average data from the 3D and highest resolution 2D histogram.

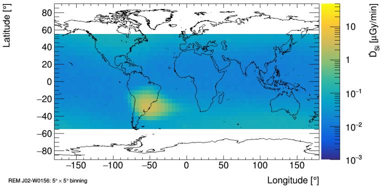
2D Histogram Database



(a) 0.5° × 0.5° bins - high 2D resolution.



(b) 1° × 1° bins - medium 2D resolution.



(c) 5° × 5° bins - low 2D resolution.

Figure 11: Average dose rates in silicon as a function of trajectory as they are generated in the backfilling algorithm between [2016-10-19 08:05:14, 2017-04-10 11:20:00).

Backfilled REM Data

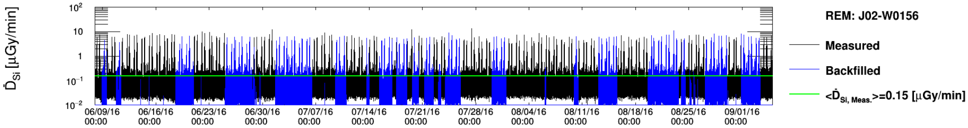


Figure 12: Dose rates in silicon between [2016-10-19 08:05:14, 2017-04-10 11:20:00); the black line represents measured data while the blue line represents backfilled data.

End result: absorbed dose rate as a function of time.

- Trajectories can be re-joined as necessary.
- GCR/SAA separation are defined by geomagnetic field intensity and Mc Ilwain L-shell.

Daily Doses

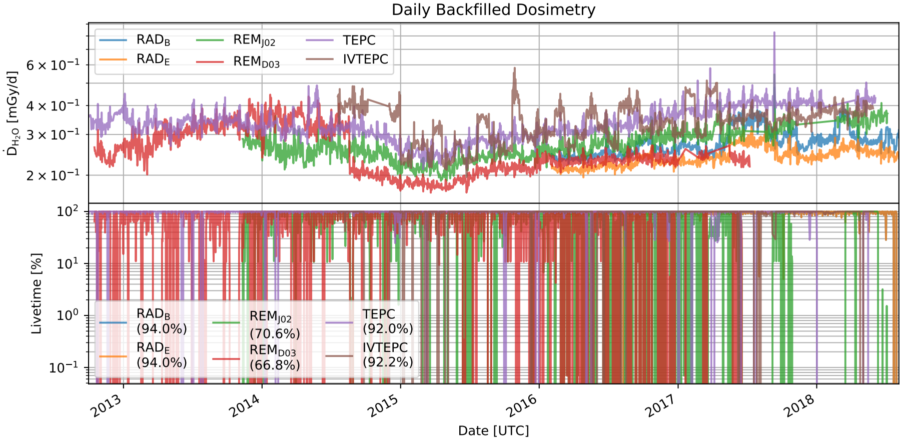


Figure 13: Daily backfilled absorbed dose in water for ISS-TEPC, IV-TEPC, RAD_B, RAD_E, REM_{D03}^{1007}, and REM_{J02}^{5001} since October 2012.

Daily LEO-GCR/SAA Doses

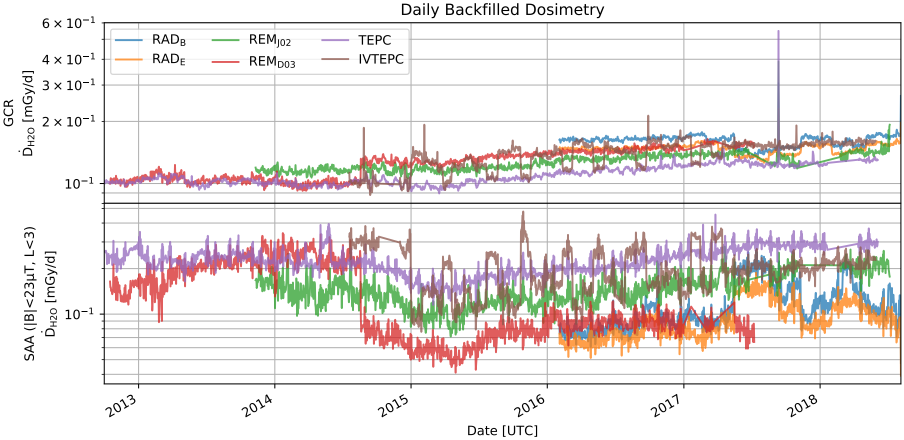


Figure 14: Daily backfilled absorbed dose in LEO-GCR and the SAA in water for ISS-TEPC, IV-TEPC, RAD_B, RAD_E, REM^{1007}_{D03}, and REM^{5001}_{J02} since October 2012.

Summary

REMs have been operating on ISS for almost 6 years and have become a valuable asset in our technology portfolio and suite of radiation instruments.

- High fidelity measurements and the downlink of raw frames allow us to refine and create new data products.
- `cron` and other *NIX utilities easily enable automation.
- Accessibility to raw data make it easy to fit into operations for post-mission assessments and reporting.

Questions?

References

[1] N. Stoffle, L. Pinsky, M. Kroupa, S. Hoang, J. Idarraga, C. Amberboy, R. Rios, J. Hauss, J. Keller, A. Bahadori, E. Semones, D. Turecek, J. Jakubek, Z. Vykydal, and S. Pospisil, *Timepix-based radiation environment monitor measurements aboard the International Space Station*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **782** (2015) 143 – 148. http://www.sciencedirect.com/science/article/pii/S0168900215001977.

[2] N. Stoffle, J. Keller, and E. Semones, *Initial Report on International Space Station Radiation Environment Monitor Performance*, tech. rep., NASA/TM-2016-219278, 2016.

[3] N. N. Stoffle, *Viability of Determining Ion Charge and Velocity Utilizing a Single Silicon Timepix Detector*. PhD thesis, University of Houston, 2014.

[4] M. Kroupa, *Timepix becoming operational in space*, Use of Timepix in Space (March, 2018) .

[5] S. George, *CRIS_L2 Algorithm Overview (v1.2)*, Internal Note (March, 2018) .

[6] M. Kroupa, N. Stoffle, C. Zeitlin, A. A. Bahadori, T. Campbell-Ricketts, and S. P. George, *Light Ion Isotope Identification in Space using a Pixel Detector Based Single Layer Telescope*, To Be Submitted .

[7] R. Gaza, *SRAG Measurements performed during the Orion EFT−1 Mission*, Workshop for Radiation Monitoring on ISS (September, 2015) .

[8] R. Gaza, *ISS Radiation Environmental Monitor (REM) Transition to Operations: RAM to REM Transition*, Workshop for Radiation Monitoring on ISS (September, 2017) .

REM2

Figure 15: Second generation Radiation Environment Monitor.

- Single Timepix sensor with a faster front-end; developed by Advacam.
  - 7+ MiniPIX units/cables certified for ISS by Oct 2018
  - 500 µm thick.
  - $E_{\Delta,pixel}$ range: 0.005 - 2 MeV.

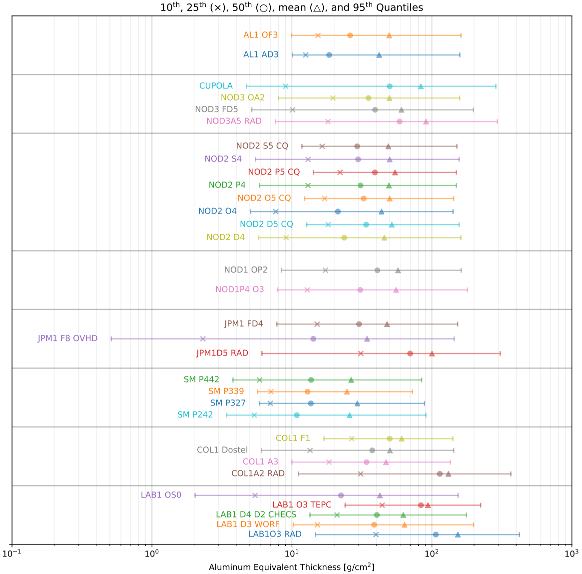
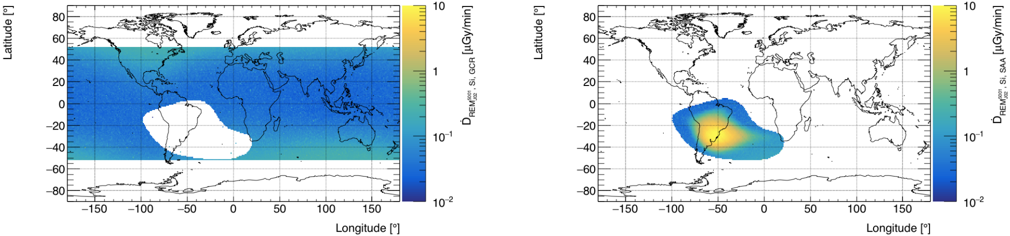


Figure 16: Statistical quantities on shielding thickness (for Aluminium) in various locations across ISS.

Dose rates for $\mathrm{REM}_{\mathrm{J02}}^{5001}$

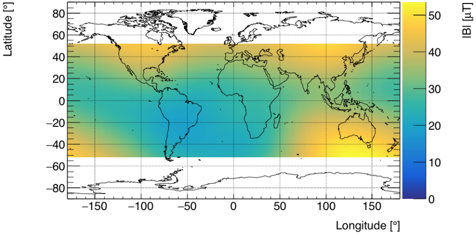


(a) $\dot{\mathrm{D}}_{\mathrm{Si}}$ in GCR.

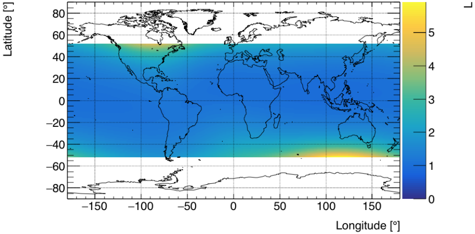
(b) $\dot{\mathrm{D}}_{\mathrm{Si}}$ in the SAA ($|B| < 23\mu T$, $L<3$).

Figure 17: Dose rate in Silicon for $\mathrm{REM}_{\mathrm{J02}}^{5001}$ as a function of trajectory for all available data measured in 2018.

|B| and L maps



(a) Geomagnetic field intensity.



(b) Mc Ilwain L-shell.

Figure 18: Geomagnetic field intensity and Mc Ilwain L-shell as functions of ISS trajectory for [2018-01-01, 2018-08-15). Parameters were calculated for each second of ISS position using Two-Line Elements from `https://www.space-track.org/`, SGP4 (Simplified perturbations models), and IGRF12 (International Geomagnetic Reference Field).