Space weather impacts of the developing South Atlantic Anomaly

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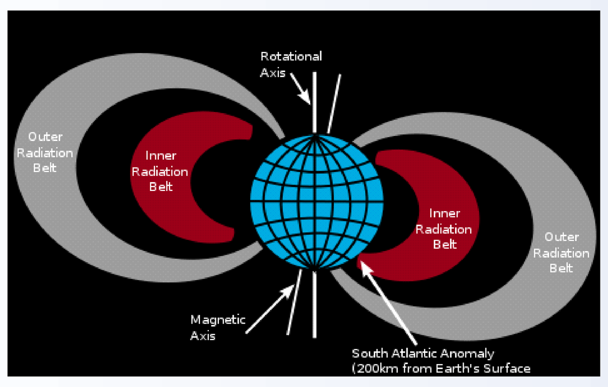
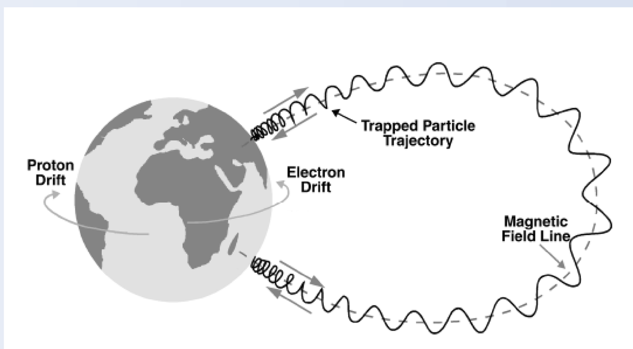
The shielding that the Earth's magnetic field provides from solar emissions and cosmic rays is significantly less in the south Atlantic and satellites that pass over the area suffer higher radiation damage. During the observation period the SAA has been deepening and growing in extent. This, combined with the decline since 1985 of solar parameters that control the shielding the heliospheric magnetic field provides from galactic cosmic rays, means that damage to satellites is expected to increase in the future.

What is the SAA?

The South Atlantic Anomaly (SAA) is a region spanning the southern Atlantic and South America where the Earth's magnetic field is at its weakest. In the SAA the field is about 1/3 the strength of the field near the magnetic poles and this affects how close to the Earth energetic charged particles can reach. What's more, the SAA is deepening - the minimum strength now is 6% lower than it was 50 years ago. Low Earth orbiting (LEO) satellites (defined as having altitude < 2000 km) are particularly vulnerable to the resulting radiation hazard.

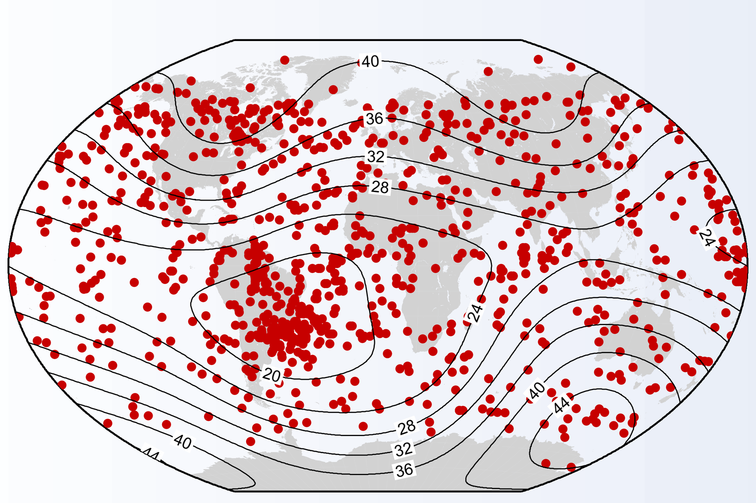
The radiation has 2 main sources: (1) trapped radiation (figures below) which originates from the Sun with the protons being the most dangerous and (2) galactic cosmic rays (GCRs) which are extremely energetic. For LEO satellites this radiation affects electronic, optical and computer systems and can also cause surface charging. These problems are worse over the SAA.

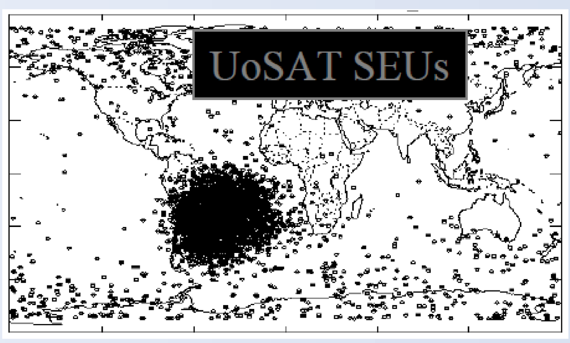




Below we show examples of satellite anomalies clustering in SAA. Left: satellite anomaly dataset anom5j.xls from www.ngdc.noaa.gov/stp/satellite/anomaly/doc/ and total intensity from model (Finlay *et al*, 2011). Right: locations of University of Surrey satellite single event upsets.

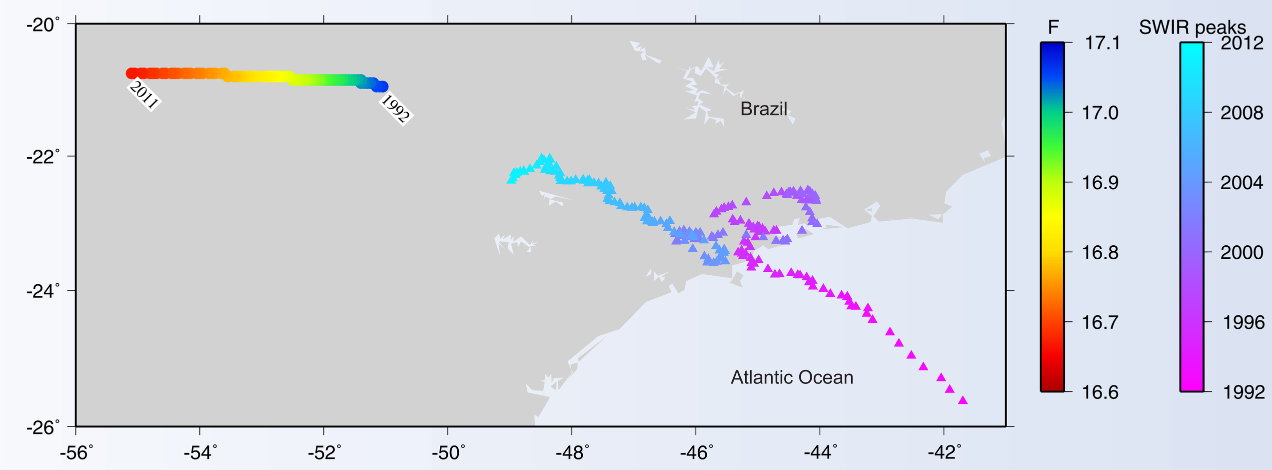
IGRF total intensity at 1990 at 800 km and NGDC satellite anomalies 1986-1992





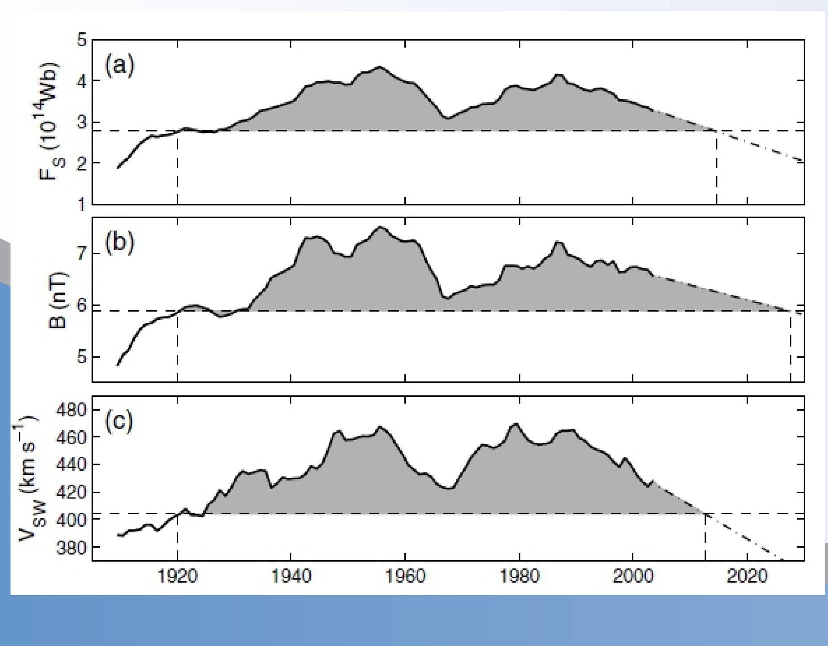
The plot below shows the westward movement of the SAA from magnetic field model (updated from Thomson *et al*, 2010) and from analysis of noise in nightside short-wavelength infrared (SWIR) radiometer data from ERS-1, ERS-2 and ENVISAT satellites (Casadio & Arino, 2011, Casadio, 2011). The deepening of the SAA can also be seen from the magnetic data. The cause of the offset between loci of magnetic field minima and SAA peaks as derived from SWIR data is not understood.

1992-2011 magnetic min (F microT) at 800 km & SAA peaks from satellite nightside SWIR data



Solar effects

The Sun is also known to also shield the Earth from galactic cosmic rays (GCRs). Solar parameters which indicate the level of protection are solar wind flow speed V_{sw}, the interplanetary magnetic field strength *B* and the open solar flux F_s. Long time-series of magnetic activity indices, in particular *aa* extending back to the 1860s, and inter-hourly variability indices, are crucial as proxies for various solar parameters (Lockwood *et al*, 1999, Svalgaard & Cliver, 2007). They extend the solar wind series derived from satellite measurements (e.g. the NASA multi-spacecraft OMNI dataset starting in 1963) back in time.

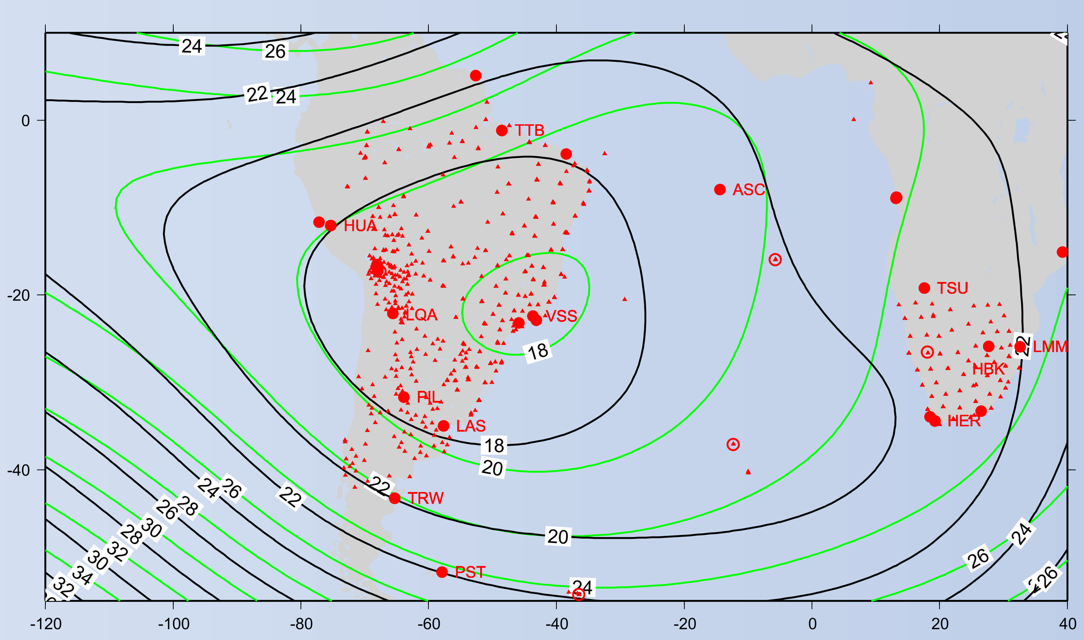


The grand solar maximum as shown by 11-year running means of (a) F_s (b) *B* and (c) V_{sw} reconstructed from magnetic indices (Lockwood *et al*, 2009). F_s is strongly anti-correlated with GCR flux. Note decrease since 1985. Solar activity and particle flux in the SAA are also anti-correlated with GCR flux as the former affects atmospheric absorption. Radiation hazard to LEO satellites may worsen in next 100 years when the Sun is expected to be less active (Barnard *et al*, 2011). However the hazard from solar emissions will be less.

Magnetic field, observations and models

The majority of the magnetic field is generated in the fluid region deep inside the Earth. Heat convection, buoyancy forces and planetary rotation cause the iron-rich fluid in the outer core to flow in a complex way and the movement of this electrical conductor through existing magnetic field generates electrical current. This current produces more magnetic field in an advective process. Some of it diffuses away resulting in a reasonably stable magnetic field which is broadly dipolar outside the planet and which occasionally reverses its polarity. The SAA may be a sign that the field is attempting to reverse.

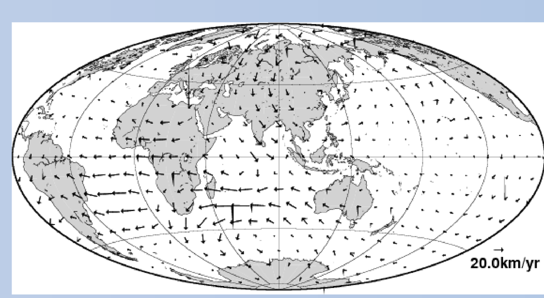
F at 800 km at 1960 (green) and 2010 (black) & sites (red) of magnetic observations 1960+



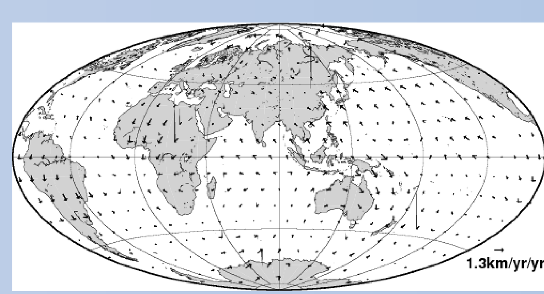
We know from observations and models of the magnetic field that the SAA during the satellite era (1960+) is growing in extent, is deepening and is moving westwards. The gufm1 model (Jackson *et al*, 2000) shows that this has been happening since 1590. Observatories are sparse in the area but recently several have been installed (red circles). The IAGA code is included for observatories with > 15 years record. Triangles show repeat stations.

But what about the future? Inverting magnetic data directly for core flow and acceleration (assuming flux is frozen which is deemed valid over the relatively short time spans of the data) and then advecting the resultant field forward in time improves forecast accuracy (Beggan & Whaler, 2010). The relatively strong westward flow in the area of the south Atlantic explains the westward movement of the SAA.

Estimated core flow at 2005 at core mantle boundary



Estimated core flow acceleration at 2005



The BGS operates ASC and PST observatories (Macmillan *et al*, 2009) and trains Navy surveyors to make repeat station observations in the South Atlantic. In Feb 2011 BGS completed the installation of a new observatory at King Edward Point on South Georgia, occupying the same site as an observatory run by the British Antarctic Survey between 1975 and 1982.

Major unknowns

- To what extent do changes in solar activity and the upper atmosphere affect radiation hazard in the SAA?
- Predictions of the Sun for next 100 years?
- What is causing the growth of the SAA?
- Predictions of the magnetic field for next 100 years?
- What is the interaction between the changing magnetic field and the charged and neutral atmosphere in the thermosphere?

These questions and others will be addressed by a bid to the recent NERC scoping study "deep Earth control on the habitable planet". Continued observation of the Earth's magnetic field from observatories and satellites, and maintenance of long-term datasets are crucial to answering these unknowns.

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