PRediction Of Geospace Radiation Environment and Solar wind parameterS

Work Package 7
Fusion of Forecast Tools

Deliverable 7.3
Forecasts of the energetic electron populations along a user selected satellite orbit

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Contents

Summary

Work package 7 aims to present the outputs/models generated within work packages 2-6 in a user friendly web interface to allow users of the system to see at a glance the current and forecast space weather conditions.

With this in mind, Task 7.3 aims to provide users with a tool to display the fluxes of high energy electrons along a prescribed satellite orbit. It makes use of the results of forecasts of the electron environment within the inner magnetosphere generated by the VERB-NARMAX Coupled model (VNC), developed in Task 6.3, to forecast the flux levels of energetic electrons.

The user selects the satellite and time period in which they are interested from an interactive web form. The Orbit Tool then determines the position of the satellite within the users time range and then searches through the results files generated by VNC, interpolating the electron flux at the satellite location and then plotting the results for the user to view.

1 Introduction

The successful and continued deployment and operation of satellite based infrastructure is heavily influenced by the local particle environment, especially in relation to the occurrence of high fluxes of medium (keV) and energetic (MeV) electrons. The dynamic nature of the electron environment within the outer radiation belt of the terrestrial magnetosphere responds to changes in the solar wind on time scales from as little as a few hours to days, with fluxes of electrons increasing by several orders of magnitude.

The resulting high fluxes of electrons can pose a significant threat to the operation of spacecraft whose orbits lie in the general vicinity of the radiation belts. Space weather events, driven by the Sun and solar wind can prematurely age satellites, cause surface charging and unwanted electromagnetic noise, affect the operation of subsystems via single event upsets, and even render them inoperable. Most significantly, this includes satellites operating at Geostationary Orbit (GEO), which lies at the edge of the nominal location of the outer radiation belt. Satellites at GEO provide key infrastructural resources such as communications, navigation (maritime, aviation, GPS), and yield detailed remote sensing and weather data that are utilised for everything from weather forecasting to agricultural pest control and the health of food crops.

Satellites are susceptible to damage resulting from the local electron population in two main ways. Medium energy electrons (10-100 keV) may result in surface charging effects, eventually resulting in discharges that can damage the surface of a satellite and its solar panels, prematurely ageing them and reducing the overall life time of the satellite. Higher energy electrons (1-10 MeV) may actually penetrate the skin of a satellite, dumping their energy within satellite electronic subsystems. Such electrons may cause effects ranging from bit flips in memory and single event upsets to damaged circuits and current overloads. While the former effects are temporary and cured by uploading another copy of the relevant software/data the latter can have serious consequences for the operation of satellites, resulting in the malfunctioning of on-board systems and even the total loss of a satellite.

The accurate and reliable forecast of changes in the fluxes of electrons in the vicinity of the radiation belts enables operators to modify their work patterns in order to mitigate the detrimental effect that these high fluxes may have on their satellites.

This Technical Note describes the development of a tool that will provide operators with estimates of the fluxes of electrons that are encountered along the track of a particular satellite orbit.

2 Overview of Methodology

The PROGRESS Orbit Tool will allow users to visualise the electron flux level experienced as a satellite orbits the Earth. This section outlines the methodologies used.

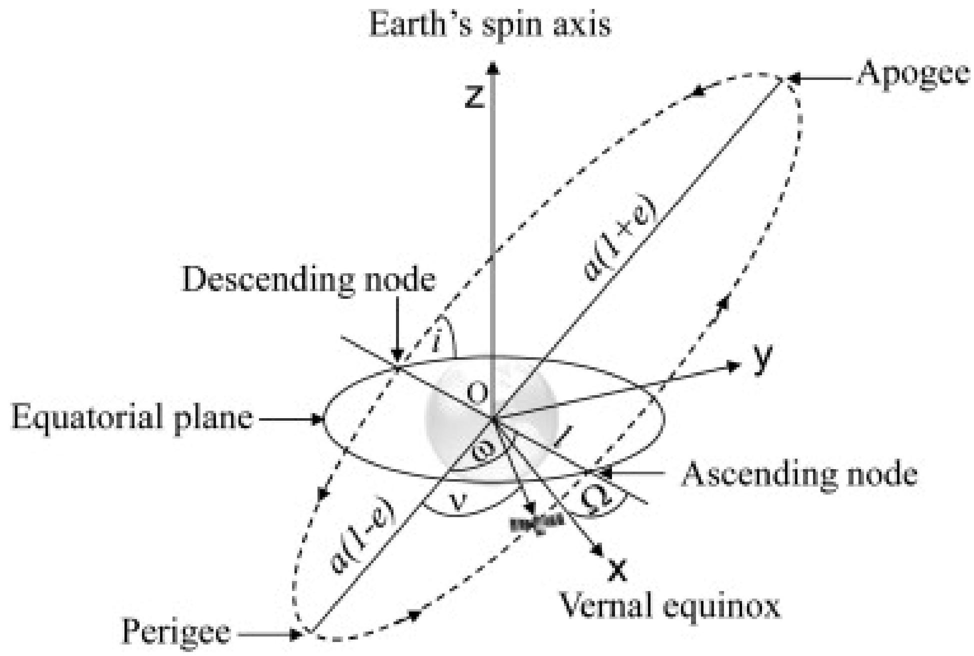

Figure 1: Diagram showing the definition of the Keplerian orbital parameters. Taken from *Trichtchenko et al.* (2014)

2.1 Satellite orbit descriptions

There are a number of ways in which the orbit of a satellite can be described. Perhaps the simplest is to utilise the set of Keplerian orbital elements to compute an orbit. This set of parameters, listed in Table 1 and shown in Figure 1 will completely characterise the orbit of a satellite assuming that the satellite moves under the influence of a uniform gravitational field and its orbit is fixed in inertial space.

However, the Earth is not a perfect sphere with a uniform mass distribution and thus its gravitational field is not completely uniform. This means that over time these parameters will change slightly, altering the shape of the satellite's orbit. It should be noted that to a first approximation the use of the Keplerian orbital elements will enable an approximate position of the satellite to be determined.

With the growth in the numbers of satellites in orbit, more accurate methods for the specification and propagation of orbits are required from an operational point of view. To enable such computations, the North American Aerospace Defence Command

Table 1: Keplarian orbital elements.

Semimajor axis	a
Eccentricity	e
Inclination	i
Right ascension of ascending node	Ω
Argument of perigee	ω
Epoch	t

(NORAD) developed a methodology for reducing the observations of a satellite orbit to a set of elements, known as a Two-Line Element (TLE) set, together with a methodology to reverse the process and reconstitute the location of a satellite using an algorithm, the Simplified General Perturbation model (SGP). The NORAD TLE's contain the mean values of the orbital elements with periodic variations removed in a specific way. It should be noted that to reconstruct the most accurate satellite locations, the orbits are required to be reconstructed in the same way in which they were originally reduced to the set of TLE elements. This process is at the heart of the SGP4 algorithm. The first release of SGP4 was described in *Hoots and Kelso* (1980), complete with an implementation in FORTRAN IV. Since then, more details regarding the equations used in the method are described in *Hoots et al.* (2004) while *Vallado et al.* (2006a,b) published a number of test and verification data sets.

The main advantage to using TLE format data rather than normal Keplerian orbital elements is simply the quantity of data available in TLE format. NORAD has the responsibility of tracking over 7500 satellites and other debris currently in orbit around the Earth. New sets of TLE's are computed on a regular basis for these objects. These TLE files are publicly available on the web at e.g. http://celestrak.com/. The data in the files is written in plain text using the following format.

```
AAAAAAAAAAAAAAAAAAAAAAAA

1 NNNNNU NNNNNAAA NNNNN.NNNNNNNN +.NNNNNNNN +NNNNN-N +NNNNN-N N NNNNN

2 NNNNN NNN.NNNN NNN.NNNN NNNNNNN NNN.NNNN NNN.NNNN NN.NNNNNNNNNNNNN
```

For example

```
NOAA 14

1 23455U 94089A   97320.90946019  .00000140  00000-0  10191-3 0  2621

2 23455  99.0090 272.6745 0008546 223.1686 136.8816 14.11711747148495
```

The first line of the TLE, referred to as Line 0, contains the name of the satellite, Lines 1 and 2 contain the TLE set of orbital parameters encoded as follows

	Line 0	
01-25	Satellite identifier	NOAA 14
	Line 1	
Columns	**Description**	**Value**
01	Line Number of Element Data	1
03-07	Satellite Number	23455
08	Classification (U=Unclassified)	U
10-11	International Designator (Last two digits of launch year)	94 -> 1994
12-14	International Designator (Launch number of the year)	089 -> March 30
15-17	International Designator (Piece of the launch)	A
19-20	Epoch Year (Last two digits of year)	97 -> 1997
21-32	Epoch (Day of the year and fractional portion of the day)	320.90946019 -> Nov 16, 1007, 21:49:37.36 UTC
34-43	First Time Derivative of the Mean Motion	.00000140
45-52	Second Time Derivative of Mean Motion (decimal point assumed)	00000-0 -> 0.0E-0
54-61	BSTAR drag term (decimal point assumed)	10191-3 -> 10191E-3
63	Ephemeris type	0
65-68	Element number	262
69	Checksum (Modulo 10)	1
	Line 2	
Columns	**Description**	**Value**
01	Line Number of Element Data	2
03-07	Satellite Number	23455
09-16	Inclination [Degrees]	99.0090
18-25	Right Ascension of the Ascending Node [Degrees]	272.6745
27-33	Eccentricity (decimal point assumed)	0008546 -> 0.0008546
35-42	Argument of Perigee [Degrees]	223.1686
44-51	Mean Anomaly [Degrees]	136.8816
53-63	Mean Motion [Revs per day]	14.11711747
64-68	Revolution number at epoch [Revs]	14849
69	Checksum (Modulo 10)	5

Using these parameters it has been estimated that the error in position may be as small as 1 km *Vallado* (2013).

The satellites supported at the time of submission of this report are listed in Appendix A.

2.2 Orbit Propagation

As mentioned above, the original release of Spacetrack Report # 3 (*Hoots and Kelso*, 1980) contained an implementation of the SGP4 algorithm written in FORTRAN IV. *Vallado et al.* (2006b) provides an update to the original report together with a set of test routines and an implementation in C++. A ReadMe file for the paper *Vallado et al.* (2006b) also provides brief details on further implementations in MATLAB, Java, and Pascal, available at http://CelesTrak.com/software/vallado-sw.asp.

For the implementation of the Orbit Tool within PROGRESS we have used the MATLAB implementation of the SGP4 algorithm. This MATLAB code, available on the web, is a line by line conversion of the C++ code written in 2005 by D. Vallado.

This code is used as is except for a few small modifications, mainly to the TLE reading routine to allow it to accept and process the information that the user supplies via the web interface. The main modifications are to reflect the fact that the user supplies the start and end times from the web GUI and the way these values are processed. Also, the satellite's orbital period is calculated from the mean motion available from the TLE and the time resolution is set such that there are 50 points calculated per orbit.

2.3 Coordinate transformations

The orbit propagation routines calculate the position and velocity of the satellite in the True Equator, Mean Equinox (TEME) frame. In this frame, the X axis lies in the direction of the the vernal equinox, the Z axis is parallel to the Earth's rotational axis and the Y direction makes up a right handed set of axes.

The electron flux data calculated by the VERB code are axially symmetric about the terrestrial dipole axis and vary in radial distance expressed as L^*, the equatorial distance of a relaxed dipole field line.

This change is coordinates is performed using a two stage process. The first converts the satellite position from the TEME frame to the Earth Centered Inertial frame (ECI) also known as Geocentric Equatorial Inertial (GEI) system. The code to do this comes from the library of astrodynamical routines for MATLAB, written by D. Vallado and available from http://celestrak.com/software/vallado-sw.asp. This transformation includes terms to take into account the nutation and precession of the Earth's spin axis.

The second transformation, to calculate L* from the GEI position of the satellite, is achieved utilising the International Radiation Belt Environment Modelling (IRBEM) library of routines via their MATLAB interface.

The Orbit Tool makes use of the *Tsyganenko* (1989) magnetic field model to calculate the L^* position of the chosen satellite. This model requires the direct input of the geomagnetic index Kp, values for which are taken from the GFZ Helmholtz Centre, Potsdam database. The Orbit Tool downloads the required Kp data on demand and then stores it for later use. Other models are available e.g. *Mead and Fairfield* (1975), or the *Olson and Pfitzer* (1974) quiet time model but were not chosen due to accuracy concerns. There are also other versions of the Tsyganenko model (e.g. *Tsyganenko*, 1995, 2002), but they require additional inputs and so have not been implemented at the current time.

2.4 Flux estimations

Estimations of the electron flux are taken from the forecasts generated by running the VNC model developed in Task 6.3 of Work Package 6. This model uses the electron flux forecasts, generated by the set of SNB^{3}GEO electron flux models developed as a result of Task 6.1 to set the VERB constraint for the electron flux at the outer limit of the simulation region. The VNC model yields a time series of the variation of electron fluxes with location (L*).

MATLAB routines, used in Task 6.3 to access the VNC output files are used to obtain the arrays of electron fluxes. Interpolation routines are then used to determine the current electron flux estimate at the location and time resulting from the orbit propagation results of the orbit propagation (time, and location, (L*)). Figure 2 shows an example of the flux

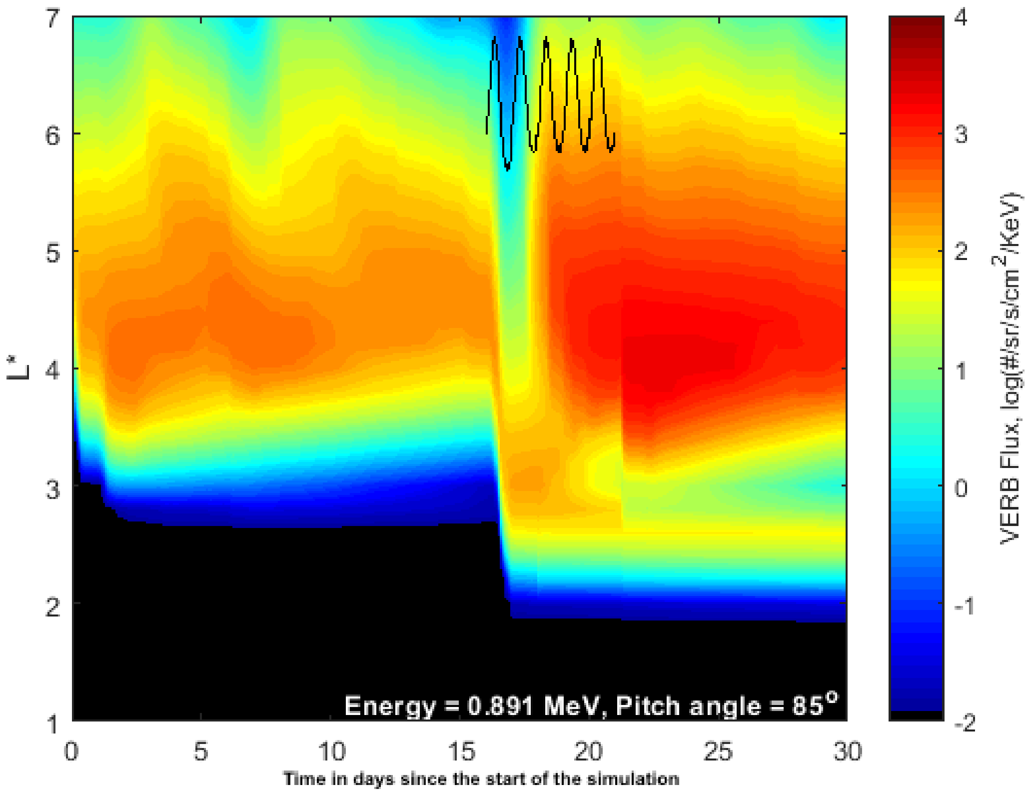

Figure 2: Electron fluxes calculated by VERB for the St. Patrick's Day storm of 2015.

variations output by VERB when running VNC during the month of March 2015.

This period includes one of the largest geomagnetic storms observed, taking place on March 17^{th}. The intensification of electron fluxes on this date is preceded by an almost complete removal of particles, the solar wind forced the magnetopause in very close to the Earth such that particles in the radiation belts found themselves connected to solar wind magnetic field lines and were lost from the system, a process known as magnetopause shadowing. The black line in the centre of the plot, just above L^*=6 shows the radial location of the SES-3 satellite operated by the company SES. The reason why these orbits looks so regular is due to the field line tracing used to calculate the L^* coordinate.

Currently Orbit Tool uses the *Tsyganenko* (1989) model, this is a semi empirical best fit representation of the Earth's magnetic field. It is based on a large number of satellite

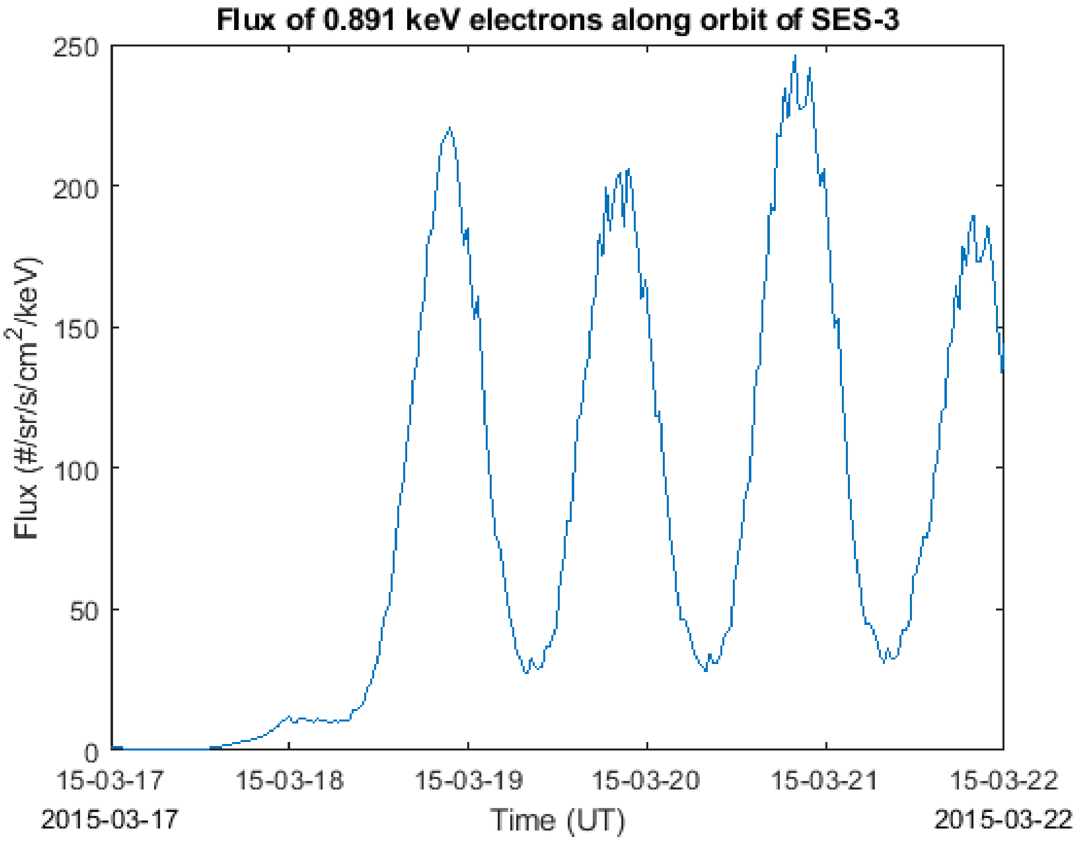

Figure 3: The flux of 0.891 MeV electrons encountered by the satellite SES-3 during the days around the St. Patrick's Day storm of 2015.

observations. It uses the geomagnetic index Kp as an input, allowing it to represent the quiet or disturbed magnetosphere, an essential quality for the Orbit Tool.

2.5 Outputs

The simplest output from the Orbit tool is a plot of the variation in the electron flux as a function of time as the satellite proceeds around its orbit. An example of such a lot for the St. Patrick's day storm of 2015 is shown in Figure 3.

It may be more useful for satellite operators to compute the cumulative electron flux or to generate an average dosage received by the satellite. These products will be further developed using input received from the PROGRESS stakeholder Committee. Currently the results outputted by the tool are (n.b. '*satellite name*' refers to the name of the satellites the user has selected, see section 4 for details):

- A plot of the VERB fluxes, with the satellites path through L^* overlaid, named '*satellite name*_verbflux.png'. An example of a similar plot can be sen in Figure 3.
- A plot of the flux encountered by the chosen satellite over the period specified, named '*satellite name*_flux.png'.
- Plots of the log and cumulative flux experienced by the satellite. These are named '*satellite name* logflux.png' and '*satellite name* cumflux.png' respectfully.
- A data file of the flux data. This contains 4 columns: time (msAD), flux (/sr/cm^2/keV), log of flux and the cumulative flux. The columns are labelled within the file, which itself is named '*satellite name* flux.txt'.
- A data file containing the orbit data called '*satellite name* orbit.txt'. The files 7 columns show the time (msAD), position vectors (x,y and z in km) and the corresponding velocity vectors (Vx, Vy and Vz in kms^{-1}). The columns are also labelled and these coordinates use the ECI system.

3 Implementation

The Orbit Tool web page is implemented in a mixture of html and PHP (as is the rest of the PROGRESS web site) alongside some JavaScript, which is used to manage display options and input validation. The users input is processed by the PHP code behind the web page. Originally, it was expected to then issue a call to MATLAB to run the orbit propagation and, flux interpolation, and plotting software application to generate the results.

However, the group that maintains the USFD web server, that hosts the PROGRESS pages, have pointed out that this mechanism allows a loop hole for the potential breech in the security of the USFD web server. We are therefore unable to implement this service through this mechanism. Two potential secure implementation mechanisms have been discussed. Both have their advantages and drawbacks.

The first is to compile the MATLAB code into an application. This should speed up the the execution of the service. However, it does mean that the web page will have to download various MATLAB libraries, of the order of several Gigabytes. This download will take quite a while, especially if the user only has access to a link with a relatively slow download speed.

The second is to set up a virtual web server for the task. Any computational jobs will then be passed on to the multiprocessor Grid computer here in Sheffield to be run as a batch job. This implies that there will be an undefined latency in the time between job submission and job execution. However, for the short job queue, this wait is typically of the order of minutes. This mechanism will also require the user to log in and enter their Email in order to identify themselves as a legitimate user.

Currently, we are setting up the second of these options since this appears to be the better methodology.

4 Operation

The Orbit Tool is accessed via the 'Orbit Tool' entry on the main navigation menu and the window shown in Figure 4 appears.

This window briefly describes the tool and the methodology used to produce plots of the electron flux around the satellite orbit. After this description, there is an HTML form that allows the user to input:

- The orbital information of the satellite of interest. This will define the path along which the electron fluxes will be interpolated. The orbit can be specified in one of two ways, which are selected via radio buttons. The users choice is between:

  1. Selecting a satellite whose TLE is available from a drop down list. This

Figure 4: Orbit Tool selection window

list is searchable for ease of use and is generated from the TLE sets currently available to the Orbit Tool. The TLE sets are updated every 2 months from the CelesTrak website. Any new satellites added to the CelesTrak sets (https://celestrak.com/NORAD/elements/) should be added to the Orbit Tool's satellite directory automatically. The previous TLE?s are not deleted and the Tool will use the most appropriate set depending on the time period entered. Thus the tool can continue to perform calculations for any time periods since its inception, for testing purposes.

2. Entering the data required, in the correct format, such that a new TLE can be constructed by the tool. This has been implemented so the Orbit Tool is still useful, even if the TLE of interest is not available. The inputs need to match those of the TLE set. This method may be used to provide data for a 'virtual satellite' to study a hypothetical orbit, but the accuracy of such a calculation is questionable due the nature of the TLE parameters. As such results from such a circumstance should only be seen as an approximation at best. If the user chooses to enter their own TLE parameters ?satellite name? in the outputs will read 'CTLE' (for Custom TLE). These parameters are not saved for future use.

- The start time of the period of interest. This should be at least one day before the current date.
- The stop time of the period of interest. This cannot be more than 2 days in the future, as that is the limit of the VNC forecast.
- The users email address. If it is a users first time using the tool they will be prompted to register their email address before they can make use of the Orbit Tool.

The user can press the 'Reset' button to clear the form if so desired. Once the satellite, start and end times and email address have been entered, the user presses the 'Submit' button and the inputs are passed to a JavaScript function for validation. This function will not allow the inputs to be submitted when: no satellite has been selected, the end time occurs before the start time or if the entered email does not match the expected format.

If the inputs meet these requirements the users selection will be pasted to the software behind the app, so it can compute the orbit and flux levels. The user will then be presented with a page which summarises their inputs, informs them that their request has been sent and where the results will be sent to. The user can then press the 'Return' button to be redirected to the original form.

As stated the users results will be sent to the email they provided. The user should be aware that in certain circumstances this may take a while since there maybe a requirement to run VNC if there is no electron flux data available for the period requested by the user.

5 Conclusions

This report has outlined development and implementation issues of the PROGRESS Orbit Tool to estimate the electron flux levels as a satellite orbits the Earth. Due to technical reasons, this tool is currently not available from the PROGRESS web interface. However, work around solutions to these problems are being sought.

Once a basic tool is in place we aim to demonstrate it to the members of our PROGRESS Steering Committee and receive their suggestions for additional products they would require to turn this application in to a useful tool for their operations.

6 Future tasks

During the development of this tool, we have come to realise that there are several parts of this tool that can be improved to yield a more realistic product. These include:

Range of Products The products shown in this report are our first ideas of plots that may be useful to those working in the satellite operations industry. This basic set will be shown to the members of our Stakeholder Advisory board in an effort to kick off discussions on what other products would be useful from an industrial point of view.

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A Current satellite lists

Table 2 contains the CelesTrak satellite TLE lists (containing approximately 700 unique TLEs) that are currently available to the Orbit Tool. The Orbit Tools data updating scripts account for any repetitions in these lists, so duplication should not occur. These can all be found on the CelesTrak website by appending the list name to the following link: https://celestrak.com/NORAD/elements/.

Table 2: CelesTrak satellite TLE lists currently availabl within the Orbit Tool

Link	List description
ses.txt	Communication satellites operated by the SES corporation
geo.txt	Communication satellites in geostationary orbit from multiple operators including: Intelsat, Telesat, Eutelsat and NASA?s Tracking and Data Relay Satellite System (TDRSS).
gps-ops.txt	Operational GPS system satellites.
galileo.txt	Galileo system satellites
dmc.txt	Disaster Monitoring Constellation for International Imaging (DMCii). These satellites provide emergency Earth imaging for disaster relief under the International Charter for Space and Major Disasters.
sarsat.txt	Search And Rescue Satellite Aided Tracking (SARSAT) system operated by the International COSPAS-SARSAT programme.
weather.txt	Weather satellites operated by the National Oceanic and Atmospheric Administration (NOAA), including the Geostationary Operational Environmental Satellite (GOES) system.
science.txt	Space and Earth Science satellites. These include: Cluster (4 satellites), Odin, Terra, Coriolis and Magnetospheric Multiscale Mission (MMS) (4 satellites) amongst others.