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Internship report

Participation to the Activities of ESTEC's Electromagnetics and Space Environment Division

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Content

Chapter 1

Introduction

International cooperation is our best reference.[1]

These words of Claude Jamar, Director General of the Centre Spatial de Liège (CSL, Belgium), summarize very well the spirit of the space field and ESA in particular. Every member of this field acts most of the time together with people from other countries.

Numerous visible examples exist: the International Space Station (ISS), where astronauts share every day their different culture at hundreds of kilometers above Earth, constitutes maybe the best one.

Nearer to us, ESTEC, ESA Research Centre in the Netherlands, counts also a lot of scientists and engineers working about various topics. One of such subjects, the validation of a simulator, was for me the occasion to get involved in this environment which is described in chapter 2. I was linked to the Wave Interaction and Propagation section where I could apply the knowledge learnt at University. Chapter 3 allows to understand my role inside that team while chapter 4 shows the use and benefits of my work. Finally a joined CD contains various documents and programs serving the goal.

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[1]Pirard T. *Rencontre avec Claude Jamar, Directeur général du Centre Spatial de Liège.* Wallonie/Bruxelles, 2006, no. 92, p 16-18.

Chapter 2

Context

2.1 European Space Agency (ESA)

The European Space Agency (ESA,[2]) was established in 1975 to replace two former European space organizations, the European Space Research Organization (ESRO) and the European Launcher Development Organization (ELDO) [6]. Its purpose is to *provide for and to promote, for exclusively peaceful purposes, cooperation among European states in the fields of* **space research and technology and space applications**.[1] It is therefore structured around a set of programmes:

- *space science*, which is the only mandatory one, with all science missions of former Horizon 2000 and next Cosmic Vision programmes, e.g. Venus Express ;

- *launcher development*, e.g. Ariane family ;

- *human spaceflight and exploration*, including the participation to the International Space Station (ISS) through the Columbus Laboratory or the Automated Transfer Vehicle (ATV) for example ;

- *earth observation*, with ERS and Envisat satellites among others ;

- *navigation*, mainly through EGNOS and Galileo projects

- and *telecommunications* (Artemis relay satellite, etc.).

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[1]Article 2 of ESA Convention

ESA gathers **17 member and 3 participating states**[2] which participate in the programmes through various ways and financial contributions leading to a total budget of about **2.9 billion €** [3]. These investments are somehow returned to them trough contracts with their industries and **more than 1900 staff** currently in post are distributed in nationality around the same ratio.

These people, which many contractors and trainees have to be added to, work in **different places**:

- the *Head Office* in Paris, France, with 375 staff ;

- the European Space Research and Technology Centre (*ESTEC*) in Noordwijk, the Netherlands, with 1075 staff, ensuring scientific and technical project management and testing ;

- the European Space Operations Centre (*ESOC*) in Darmstadt, Germany, with 276 staff, for satellite operations ;

- the ESA Centre for Earth Observation (*ESRIN*) in Frascati, Italy, with 167 staff, taking care of earth observation, data processing and distribution ;

- the European Astronaut Centre (*EAC*) in Köln, Germany, with 16 staff, the astronaut training centre ;

- the Centre Spatial Guyanais (*CSG*) in Kourou, French Guiana, Europe's spaceport for Ariane launches,

- and various offices and ground stations all over the world.

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[2]The members are Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom. Cooperation agreements allow Canada, Hungary and the Czech Republic to participate in some projects.

Figure 2.1: ESTEC (Credits: ESA)

The Agency is managed by a Director General elected every 4 years, for the moment, Jean-Jacques Dordain, and divided into 9 **directorates** designated by 3 letters e.g. TEC for the Technical and Quality Management directorate or EUI for the European Union and Industrial Programmes directorate. Themselves are divided into departments (one letter), divisions (one letter) and sections (one letter).
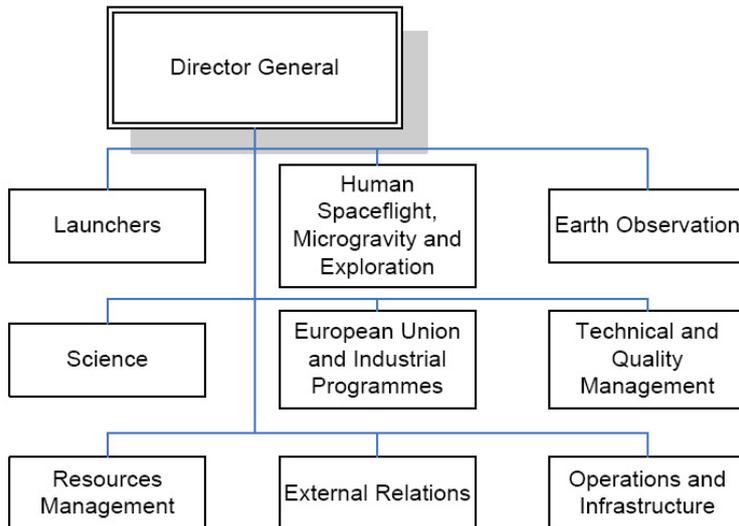

Figure 2.2: ESA structure

2.2 Electromagnetics and Space Environment Division (TEC-EE)

The Electromagnetics and Space Environment division (TEC-EE) is part of the Electrical Engineering Department of the Technical and Quality Management directorate (**TEC**). This directorate gathers **expertise in many fields** and puts it at disposal for any mission leaded by the other directorates.
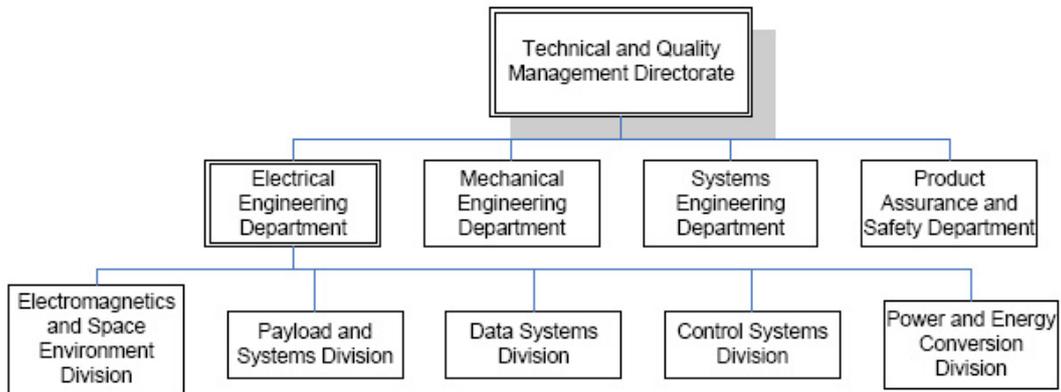

Figure 2.3: TEC-EE position

The TEC-EE division is responsible for

- antenna systems through its Antenna and Sub-Millimetre Wave section (TEC-EEA),

- electromagnetic compatibility with the ElectroMagnetic Compatibility (EMC) and Antenna Measurement section (TEC-EEE),

- electromagnetic wave interactions and propagation through the Wave Interaction and Propagation section (TEC-EEP)

- and space environments and effects with the Space Environments and Effects section (TEC-EES).

For my internship, I was welcomed by the **TEC-EEP** section composed of 9 people [4]. They are involved in several projects dealing with propagation of microwaves through the troposphere and ionosphere, and interaction of microwave and optical signals with the surface of the Earth and other planets. For example, they are undertaking research for Earth Observation as well as Science (Bepi-Colombo mission) or Navigation projects (EGNOS and Galileo). They are then brought into contact with internal people, for instance, from the Galileo Project (EUI-NG) and external groups from industries or research bodies.

The section concern for Galileo treats about the **atmospheric effects on navigation signals**. They have been classified in three groups:

- *tropospheric effects* among which delay,

- *ionospheric effects* among which delay

- and *local environment effects* among which multipath.

I was linked to the **ionosphere** part dealing with the delay created by ionospheric electron content. This delay is crucial because of the consecutive relatively high range error ($10m$ on average) taking into account Galileo's planned accuracy (less than $1m$).

2.3 Objectives

To consider and study the impact of atmospheric effects, different **models** are used. One of the models used for the ionospheric effects is called **NeQuick** and is included into simulators and receivers software. One issue is then to **check** if the **implementation** of the model is correct in these devices.

In this framework, contacts are held with the Radio Navigation section (TEC-ETN), ESTEC's Radio Navigation Laboratory [5] and several industrial partners.

Figure 2.4: Radio Navigation Laboratory (Credits: ESA)

I have been involved in these contacts about the tests and validation of the ionospheric models implemented in a Galileo Signal Simulator (cf. chapter 4). My work consisted in writing a number of FORTRAN programs and routines that makes use of NeQuick model (cf. chapter 3) in order to produce modelled values to compare with simulations.

By integrating the electron density from NeQuick along a ray joining one particular surface station to a set of Galileo satellites possible positions, the program gives slant total electron contents of ionosphere for different predetermined stations.

Chapter 3

Analysis

3.1 Baseline

3.1.1 NeQuick model

NeQuick is an ionospheric model based on the **Di Giovanni and Radicella (DGR) approach** developed in Trieste, Italy, from 1990 and later in Graz, Austria [9]. It has been recommended by the Radiocommunication Sector of the International Telecommunications Union **ITU-R** from 2002 for transionospheric propagation[1].

This empirical model is called a "**profiler**" because it uses the peaks of ionospheric layers E, F_1 and F_2 as anchor points. To obtain their characteristics (height and amplitude), it employs ionospheric parameters from the ITU-R (CCIR[2]) maps for critical frequency foF_2 and transmission factor $M(3000)F_2$ and modified maps similar to the ITU-R ones for critical frequencies foE and foF_1 [8].

The version published by the ITU-R is built in FORTRAN and is divided into **two components**:

- the *bottomside* i.e. the height region below the peak of the F_2 layer, based on the above-mentioned anchor points and derived thickness parameters (e.g. figure 3.1)

- and the *topside* for the above region, which uses a height dependent thickness parameter (e.g. figure 3.2).

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[1]Downloadable [7] or on joined CD in "Tools" directory
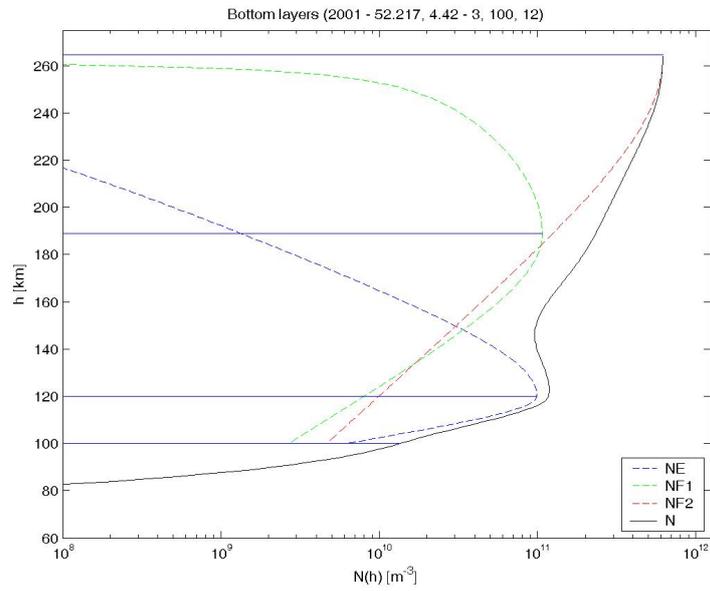[2]Consultative Committee for International Radio, former ITU-R

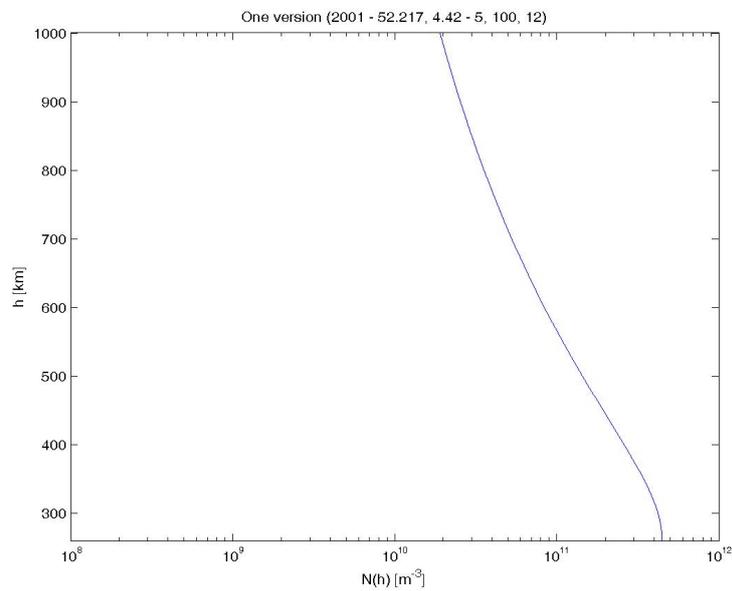Figure 3.1: Bottomside profile example (ESTEC location – $52.217°N$, $4.42°E$ –, March, average solar flux – 100 –, midday)

Figure 3.2: Topside profile example (ESTEC location – $52.217°N$, $4.42°E$ –, March, average solar flux – 100 –, midday)

Its **input** values follow the main ionospheric variables:

- *space* with height h [km], latitude *alat* [$°N$] and longitude *along* [$°E$],

- *season* through month *mth*,

- *solar activity* with monthly mean of solar radio noise flux at about $10cm$ wavelength $F10.7$ *flx* [$10^{-22}\ W\ m^{-2}\ Hz^{-1}$][3]

- and universal *time ut* in hours.

It gives electron density in electrons per cubic meters ($el.\ m^{-3}$) as an **output**.

3.1.2 eldens and slQu drivers

Associated to NeQuick and published in the same package, eldens and slQu drivers allow to **use NeQuick**, which is only a function, in various ways by asking input data to the user.

- eldens gives *single values of electron densities and height profiles.*

- slQu extends the possible calculations to *slant profiles and total electron contents (TEC [$el.\ m^{-2}$][4]).*

A scheme of slQu structure is proposed in figure 3.3 on the basis of its constitutive functions and subroutines.

Two subroutines ensure **input** operations.

- rays asks for *space* conditions (upper left part in blue) i.e. ray endpoints coordinates and calls then naut to calculate ray perigee properties and zenith angle and gcirc to get the properties of the great circle between ray endpoints, mainly azimuth.

- dat_t_sa takes care of the other conditions (*date, time and solar activity* ; lower left part in green) and is followed by NeQuick initialization to these conditions. Entry points eldens and vert can then be used only with space input values (dotted arrows).

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[3]The exact variable to be used is the 12-monthly smoothed flux or equivalently the 12-monthly smoothed sunspot number, R_{12}.

[4]A more useful unit for TEC is the TEC unit.

$$1TECu = 10^{16}el.\ m^{-2}$$

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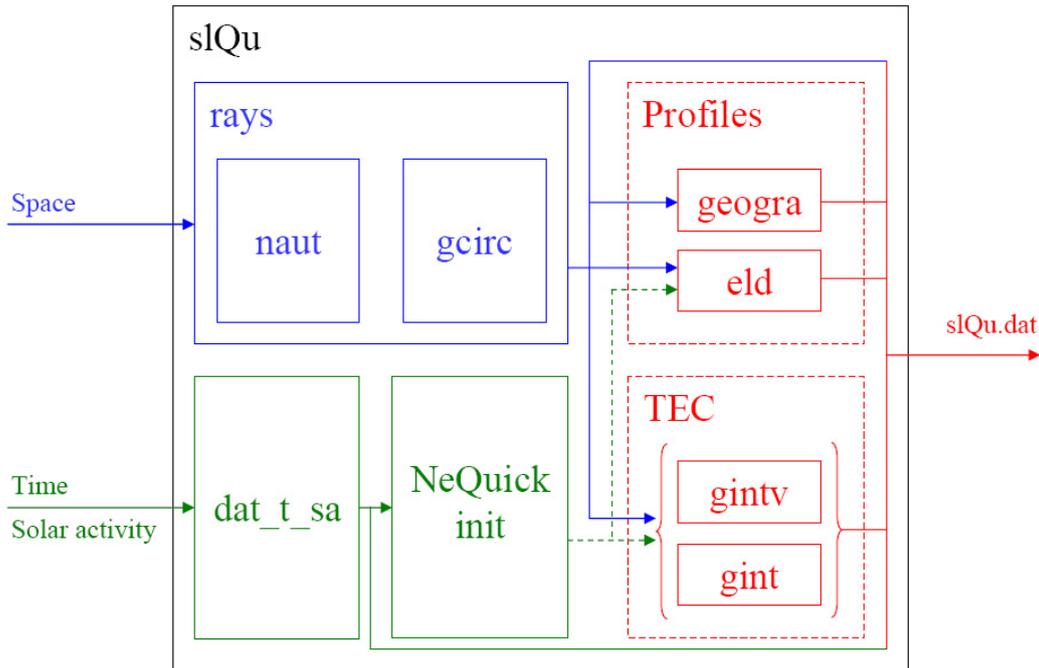
Figure 3.3: slQu structure

The program is then divided into **two parts** according to its two different uses (right part in red).

- The *slant profiles* calculation is held by geogra subroutine and eld function. The first gives height and geographic coordinates of successive points along the ray from its coordinates (zenith angle, azimuth and distance from perigee). The second computes electron density at the same points from the same parameters.

- To generate *TEC* values, numerical integration functions gintv for vertical situations and gint else are called. They are based on second order Gauss-Legendre quadrature.

Finally all the **results** are stored into the file slQu.dat.

3.2 Work description

3.2.1 Task structure

The understanding leading to the description in section 3.1 constituted the first part of my work which I divided into **several steps taking into account team working** features as I was working with my supervisor and with people from the Radio Navigation Laboratory.

I proposed to split the basic question "How to compare simulated values with modelled values?" defining the objective into 4 not necessarily time successive issues (cf. figure 3.4).

- First of all it was necessary to choose relevant various *input conditions* (cf. subsection 4.2.1) which was my concern. It was intended to work with different surface points (called Galileo Sensor Stations (GSS) in the following) receiving signals from different in-sight satellites i.e. considering different rays to different higher endpoints at the same height.

- The people in charge for the *simulator* could then run it with them.

- My main role was to build the software to *gather modelled values*. As slQu was only giving TEC along one ray at a time and was managing input operations in a too simple, manual way, it was necessary to modify it for this purpose. It was also necessary to use some other programs to watch results as it was not very efficient just to read DAT files.

- Finally the *comparison* could be held with my supervisor.

I consequently created **two packages**[5].

- sTECGSS is designed to compute *complete sets* of slant TEC (sTEC) values for one station covering a specified area in the sky (cf. subsection 3.2.2).

- delGSS is intended to use *specified sets* of station-to-satellites links and to give the corresponding range error or delay (cf. subsection 3.2.3).

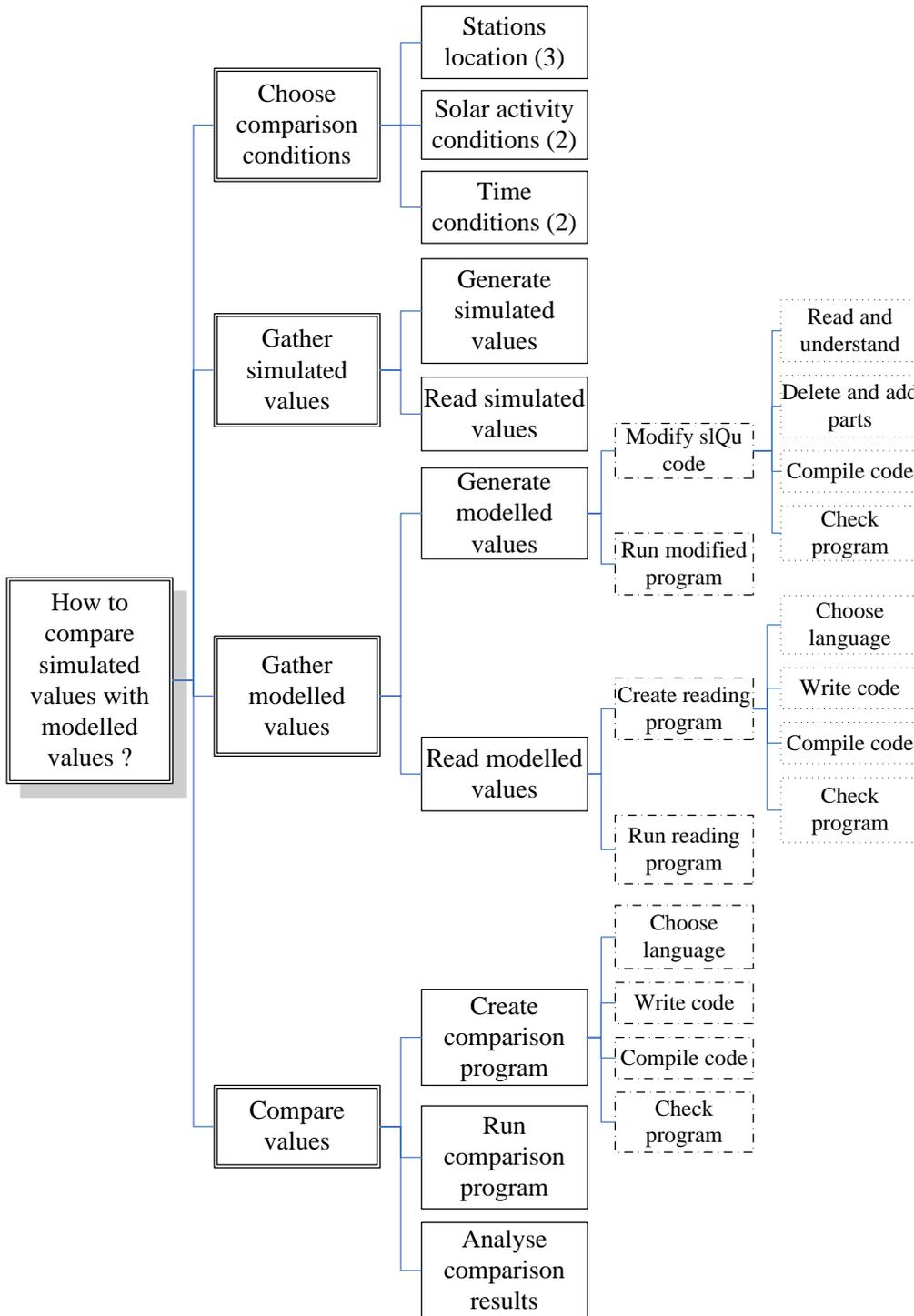[5]On joined CD into "Release" directory.

Figure 3.4: Task structure

3.2.2 sTECGSS package

This package is built from an approach similar to slQu second part for each TEC calculation with a **loop on satellite position**. The main difference from the original driver consists in the primary use of azimuth and elevation to define a ray instead of higher endpoint latitude and longitude which have to be calculated (by means of geogra subroutine). naut subroutine consequently turned into per subroutine (cf. figure 3.5).

The *main* program, sTECGSS, calls two secondary subroutines depending on wanted results format.

- sTECGSSm (m for *man*) stores the output values into a TXT file including remembering of input characteristics at the beginning and column titles. The name of the file also depends on current location, year, month, time and sunspot number.

- sTECGSSe (e for *Excel*) gives the rough numbers i.e. without column titles, etc. but adds in first columns input data corresponding to each TEC value. The name of the output file is asked.
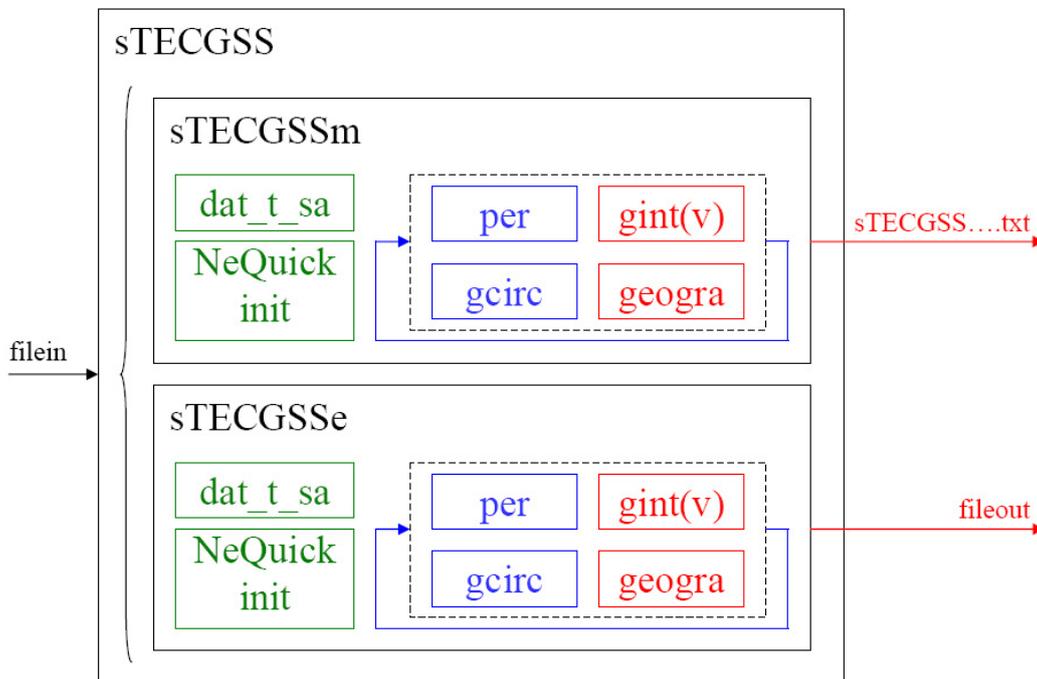

Figure 3.5: sTECGSS structure

The program reads the needed **input** values from a file which name is asked. It contains

- *station* characteristics (name, latitude and longitude - height is assumed 0),

- *time* characteristics (year, month, local time and separation from GMT)

- and *solar activity* characteristics (parameter type and value).

Satellite possible positions characteristics (height, kind of grid, lowest elevation, maximum angles step or number of angles steps) have to be directly given by the user.

For our purpose, another program, sTECGSSdemo, with **predefined values** of the latest parameters (Galileo satellites altitude of 23222 km, constant angles steps of 10° and lowest elevation of 10°) was created. It is associated with two Excel files, one to create the input file and the other to visualize the results by means of radar plots (one curve for each value of elevation in polar coordinates with TEC as radius and azimuth as angle).

Figure 3.6 shows an example of such a plot. Two interesting features are noticeable:

- the increasing TEC values with decreasing elevations because of the increasing ray path into the atmosphere

- and the azimuth of TEC maxima corresponding more or less to the direction of the sun.
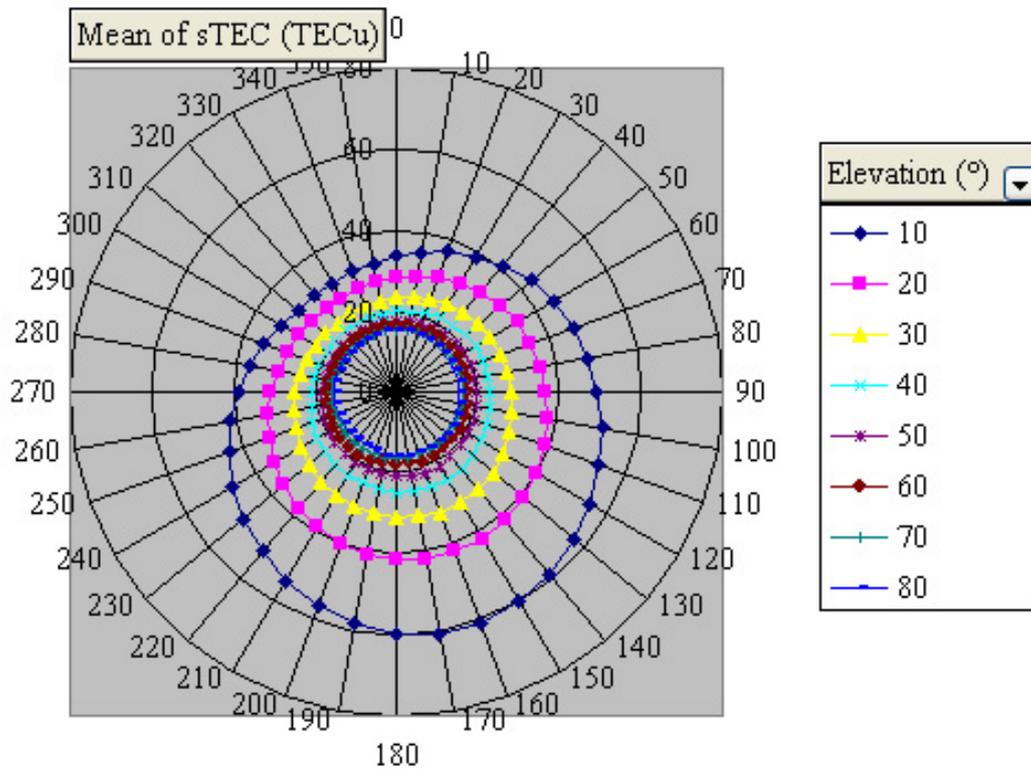
Figure 3.6: Radar plot example (ESTEC location – $52.217°N$, $4.42°E$ –, March, average monthly smoothed sunspot number – $R_{12} = 50$ –, 13h local time)

3.2.3 delGSS package

In order to compare with the values from the simulator, sTECGSS was **transformed** to delGSS.

- As the simulator is considering different satellites which position evolves with time, it was better to run the model only for some *specific station-to-satellite links* (i.e. azimuth, elevation and UT values).

- According to the goal of validating the model implementation into the simulator, some *post-processing operations* were desired so that only the possibility for Excel dedicated output was maintained.

- The simulator is giving the *range error*[6] related to ionospheric delay and the same variable was preferred to sTEC for output from the model.
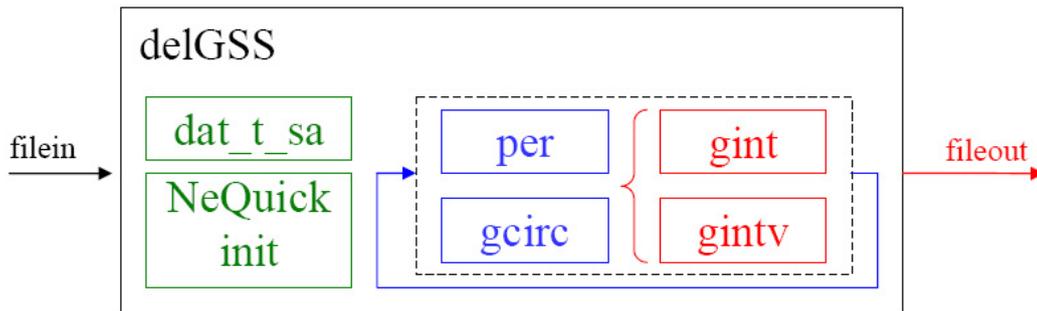
Figure 3.7: delGSS structure

The same **predefined values** as for sTECGSSdemo were selected to build delGSSdemo also associated to two Excel files, one related to input and the other to the results. The corresponding range errors are subtracted and means and standard deviations are calculated for each set of input conditions.

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[6]The relation between TEC and the ionospheric range error depends on the frequency in the following way (TEC in *el. m^{-2}* and f in Hz).

$$\Delta s[m] = 40.3 \frac{TEC}{f^2}$$

$1 TECu$ corresponds approximately to an error of $0.16m$ for L1 at about 1.5 GHz.

Chapter 4

Comparison

4.1 Simulator

In order to build receivers and tools dedicated to Galileo system ready for its operational phase, ESA got involved into the development of the **Galileo Signal Validation Facility** (GSVF) with Thales Research and Technology (TRT, UK) as industrial partner. This project was divided into two phases, the first (GSVF1) to develop a simulator and receiver test-bed and the second (GSVF2) focused on the implementation of latest signal modification proposals in the simulator named Galileo Satellite Constellation RF Signal Simulator [1].

The latest fulfills two important **roles**.

- Before the signals in space are available, it allows the *development* of receiver equipment.

- It provides a *validation* tool for functionality and performance of receivers.

It is designed to **reproduce** the signals to be received from orbiting satellites and following systems and atmospheric effects:

- the *relative motion* of satellite and receiver platforms,

- the satellite *clock* uncertainties including relativistic effects,

- the characteristics of satellite and receiver *antennae*,

- *ionospheric and tropospheric* propagation

- and *shadowing, blockage and multipath* environment of the receiver.

It represents the **constellation** in terms of

- generated *RadioFrequencies* (RF) – E5, E6 and L1 (cf. number of devices in the left part of the simulator in figure 4.1) –

- and *available satellites* – up to 48 can be considered depending on scenario.

Figure 4.1: Constellation RF Simulator (Credits: ESA)

The simulator takes advantage of different **software and hardware tools** among which digital signal processing (DSP), field programmable gate arrays (FPGA) and RF hardware. Its flexibility and configurability are increased by a comprehensive windows-based Graphical User Interface (GUI).

4.2   Results

4.2.1   Conditions

In order to validate the implementation of the model into the simulator, it was important to obtain different orders of error by choosing **various** sets of input conditions (cf. figure 4.2) in

- *latitude* (mid latitude: ESTEC – $52.217°N$, $4.42°E$ – ; lower latitude: Palermo – $38.167°N$, $13.083°E$ –; higher latitude: Reykjavik – $65.117°N$, $-21.883°E$),

- *solar activity* (average monthly smoothed sunspot number: $R_{12} = 50$; highest monthly smoothed sunspot number: $R_{12} = 150$),

- *time* (day: 12 UT ; night: 0 UT)

- and *signal frequency* (E5: $1191.795 \; MHz$; E6: $1278.95 \; MHz$; L1: $1575.42 \; MHz$).

Scenario	Station	Month	Initial UTC	Sunspot number	Frequencies
1	ESTEC				
2	Reykjavik		12		
3	Palermo			50	
4	ESTEC				
5	Reykjavik		0		
6	Palermo	3			E5 E6 L1
7	ESTEC				
8	Reykjavik		12		
9	Palermo			150	
10	ESTEC				
11	Reykjavik		0		
12	Palermo				

Figure 4.2: Input conditions

4.2.2 Validation

After having met the people from the Radio Navigation Laboratory in order to agree on the procedure, we received the results in XML files that we translated to Excel files. These were used with delGSSdemo program in order to obtain modelled range errors[1] which vary between following **extreme values**.

- The *minimum* value, $1.475m$, corresponds as expected to low ionization conditions (situation 2 – low solar activity: $R_{12} = 50$; higher latitude: Reykjavik ; short ray in opposite direction to the sun: elevation $= 60.5°$ and azimuth $= 246°$ – and highest frequency L1).

- Opposite conditions bring a *maximum* value of $53.814m$ (situation 9 – high solar activity: $R_{12} = 150$; lower latitude: Palermo ; long ray towards the sun: elevation $= 21.2°$ and azimuth $= 183.7°$ – and lowest frequency E5).

Scenario	Mean difference (m)	Standard deviation (m)	Max difference (m)
1	0.0028661	0.001872984	0.02543281
2	0.0093746	0.011925361	0.113573238
3	0.0183213	0.020667544	0.110990042
4	0.0107107	0.008420781	0.047003032
5	0.008608	0.006731935	0.041082666
6	0.0195208	0.017890999	0.067730174
7	0.0439163	0.019709702	0.09825972
8	0.017133	0.010873819	0.059025258
9	0.054734	0.033546873	0.163040895
10	0.017489	0.012618355	0.052739417
11	0.0227398	0.01249828	0.060918838
12	0.0240483	0.01198413	0.052796395

Figure 4.3: Comparison of absolute values

The **absolute difference** equals $2cm$ on average and $16cm$ for maximum value which is very low regarding to the absolute values higher then $1m$.

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[1]All these files are included on the CD into "Results\del" directory.

Scenario	Mean relative error (%)	Std dev relative error (%)	Max relative error (%)
1	0.051943302	0.029185333	0.463587553
2	0.213116633	0.236170375	1.975234627
3	0.054303236	0.049761428	0.237113463
4	0.361172075	0.336587282	1.568302901
5	0.292965885	0.274147589	1.412648669
6	0.454804225	0.416722211	1.316402103
7	0.322899676	0.181728391	0.65279173
8	0.211400385	0.082797191	0.380558906
9	0.197629224	0.081707442	0.399131718
10	0.281555631	0.176454735	0.538029798
11	0.371948613	0.153113336	0.862518013
12	0.340932536	0.143304645	0.634866936

Figure 4.4: Comparison of relative values

The analysis of **relative difference** confirms the former conclusion: less than 0.5% on average and all the time below 2%.

The GSVF2 implementation of NeQuick is then considered to be **correct**.

Chapter 5

Conclusion

Working at ESA was a really exciting and enriching experience.

As soon as I arrived, I was considered as a **collaborator**. I was advised to take the most advantage of my internship by going to conferences or asking any question I could find interesting because I had also to think for myself. And I have not been deceived as much as for my personal interest than for research for professional purpose or for my work inside this organization.

I could indeed **learn** a lot about various projects as distributed computing or biomimetics. Every time I wanted to have some opinion or explanation about a topic, the people around me – especially my tutors and head of section, Roberto Prieto Cerdeira, Antonio Martellucci and Bertram Arbesser-Rastburg, towards who I am very grateful – were always ready to help me and proposed me often their support.

As a consequence, I had access to all information I found relevant to achieve the goals of the internship and I was also **free** to organize my work as I wanted. This constitutes the best way to realize efficient work and makes you willing to give the best of yourself. So I was trying to act as a member of the team by taking various initiatives.

This interaction implies to be aware of the understanding of your interlocutor about the subject you are explaining and to convert the work of your collaborator into useful and accessible tools for others. This sense of the **link** is very important and interesting: provide colleagues with the link to the right person for their needs, ensure the link between research centres, universities and industry, etc.

The job described in this report constitutes a good example of the above-mentioned characteristics. It concerns the result of **team working** between scientists and engineers from different origins, research centres and industry, and from different countries.

This international environment makes people open-minded, ready to consider with you tremendous projects and to lead you behind your limits so that **everything becomes possible**.

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