FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Signals of Opportunity in Low Earth Orbit

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Resumo

O objectivo principal desta dissertação é avaliar a suficiência de sinais de oportunidade para navegação em baixas órbitas (LEO) e para tal um estudo preliminar sobre os requisitos de precisão a ter em conta foi feito. Vários tipos de sinal serão então estudados de modo a verificar se os requisitos são satisfeitos, também para avaliar a viabilidade do uso de sinais de oportunidade como DTTV e LTE existentes nas altitudes de baixa órbita na Terra e quantificar a disponibilidade de transmissores face aos obstáculos existentes. Um dos muitos problemas existentes na área aeroespacial é a navegação assistida. Os receptores GPS utilizados actualmente nos satélites LEO são demasiado caros e uma grande parte do orçamento total é usada para comprar esses componentes. Nesta tese será feita uma avaliação da possibilidade de estimar a trajectória de um satélite e desta forma descobrir as condições que o podem reduzir. Algumas destas condições a ter em conta que podem restringir o resultado são a taxa de observações necessárias e a disponibilidade de estações com transmissão de potência e multifrequência suficientes. Realizou-se um estudo sobre esses aspectos e posteriormente uma implementação de um Filtro de Kalman juntamente com os dados recolhidos sobre a existência de transmissores e, analisando o erro em função do número de estações e do tempo, será possível retirar conclusões acerca da possibilidade de navegar. Devido à falta de tempo, apenas os transmissores DTTV foram estudados nesta tese, deixando outros para trabalhos futuros a serem feitos. Apesar disso, os resultados foram bastante satisfatórios e suficientes para abrir portas para a futura implementação deste sistema num sistema de tempo real num satélite.

Abstract

The goal of this dissertation is to assess the sufficiency of signals of opportunity for navigation in low earth orbits (LEO) and for that effect perform a preliminary study concerning availability requirements for successful navigation in orbit. A number of signal types will then be studied in order to verify requirement satisfaction, also to assess the feasibility of using signals of opportunity such as DTTV and LTE existent at Low Earth Orbit altitudes. One of the many problems in the aerospace domain is assisted navigation. GPS receivers used in LEO satellites are very expensive and a big part of the total budget is used to buy these components. Some of the conditions that could constraint the result would be the rate of observations necessary and the availability of stations with sufficient power and multifrequency transmission. A study regarding these aspects was done and later an implementation of a Kalman Filter with the transmitter information data that, by analyzing the error in function of the number of stations and time, allowed for conclusions to be taken. Due to lack of time, only DTTV transmitters were studied in this thesis, leaving others for future work to be done. Despite that, the results were quite satisfactory and prove there's a good scenario for the future implementation of this system in a real time system in a satellite.

Agradecimentos

Quero exprimir os meus sinceros agradecimentos ao meu orientador Sérgio Cunha pelo tempo e interesse ao qual já me habituou ao longo do meu percurso académico. Ao Américo, Bruno e Nuno pelas referências não referenciadas e ao Bruno especialmente pela relação simbiótica que nos permitiu mantermo-nos sanos ao longo do semestre. À família no geral pelo apoio subentendido e espcialmente à minha mãe por conseguir lidar com a calendarização peculiar do desenvolvimento desta tese.

David Leite

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Abbreviations and Symbols

COCOM	Coordinating Committee for Multilateral Export Controls
DTTV	Digital Terrestrial Television
EIRP	Effective Isotropic Radiated Power
EOS	Earth Observation Satellite
LEO	Low Earth Orbit
GNSS	Global Navigation Satellite Systems
MFN	Multi-Frequency Network
MIEEC	Mestrado Integrado em Engenharia Electrotécnica e Computadores
SoO	Signals of Opportunity
SNR	Signal to Noise Ratio
TDoA	Time Difference of Arrival
TLE	Two Line Element

Chapter 1

Introduction

One of the many problems in the aerospace domain is assisted navigation. GPS receivers used in LEO satellites are very expensive and a big part of the total budget is used to buy these components. Assisted navigation is a topic of much interest because GPS receivers that are currently used in LEO satellites use too much of a large quantity of the total budget of projects. That's where this thesis theme becomes interesting, because using Signals of Opportunity for navigation is a much cheaper option where the large global availability of these signals is a very attractive aspect. Additionally the fact that some of these signals are digital, like DTTV, makes the reconstruction of the originally transmitted signals much easier than for analog signals.

This curricular thesis, due to the last semester of the last year of the Integrated Master in Computer and Electronics Engineering at the Faculty of Engineering of Porto, was guided by the faculty's Assistant Professor Sérgio Reis Cunha PhD, who have been present pedagogically throughout the author's extracurricular projects that triggered the interested in this theme in the first place. It focuses on the state of the art around the thesis' theme, the objectives - that are a division of the theme in more achievable tasks - and the motivation, what are the potential applications and their intrinsic benefits.

1.1 Context

A concept that is important to introduce is that of signals of opportunity. Being primarily used for other purposes, such signals are, by their availability and their characteristics, suitable for performing measurements just by being received. It is an objective to use certain broadcasted signals for Low Earth Orbit (LEO) satellites navigation establishing a navigation system similar to GPS, that can be used in flight from low to very high altitudes, including possible use on LEO satellites.

1.2 Objectives

The main goal of this dissertation is to assess the feasibility of using SoO for navigation in LEO satellites by elaborating a preliminary study. The aspects that will determine the minimum requirements for this assessment will revolve around the different LEO common trajectories, the availability of different signals that gather a set of interesting characteristics for this purpose and the possibility of implementing a Kalman filter for trajectory estimation. Additionally a link budget research of the existing LEO satellites will have to be done regarding detectability in orbit with sufficient SNR, by studying already existing data and articles. Also, orbit propagation methods will have to be studied and develop an algorithm that estimates trajectories and possibly satellite behaviors when performing maneuvers.

1.3 Motivation

The author's contact with the subject of signals of opportunity and their applications in navigation have started in late 2015 when an application for the REXUS/BEXUS programme (component BEXUS) was first submitted with the team SIGNON (Signals of Opportunity for Navigation), experiment that was followed, the year after, by another REXUS/BEXUS application, this time for the REXUS component of the programme, with the team SPAN. The interest was there and, after attending a Space Engineering class as a minor of the MIEEC course, it only grew; this thesis theme seemed only appropriate.

Chapter 2

State of the art

Most satellite navigation methods are GPS based or if not available, dedicated ground signals. There have been great results (centimeter accuracy) achieved using dual-frequency GPS receivers aboard[1]. But for smaller satellites, the single-frequency receivers are more suitable since they are more cost and energy effective. Amongst the receivers currently in mission are: the TOPSTAR 3000 receiver aboard the Korea multi-purpose satellite-2 (KOMPSAT-2), and the Phoenix receiver on PROBA-2. But although GPS is a proven radio signals based navigation system, its use in orbital conditions is not as straightforward. Both COCOM restrictions regarding altitude and speed [2] and the increased Doppler shift due to LEO dynamics, require resorting to specific receivers in orbit, which are not so energy and cost effective as their low dynamics counterparts. Navigation based on other signals may provide more effective solutions in certain applications. GPS receivers used in LEO satellites are very expensive, and a big part of the total budget is used to buy these components. In addition, GNSS signals are prone to jamming and being interrupted[3].

Low Earth orbits (LEO) are all geocentric orbits with altitudes between 180 and 2000 km and with orbital periods between about 84 and 127 minutes, where the speed the satellite travels is mostly a consequence of its altitude due to the Earth gravitational pull. Most LEO satellites have as purpose performing a scientific experiment or doing measurements or even taking pictures: the PROBA from ESA, which is still in mission is taking high quality pictures of the Earth, the Aqua satellite, developed by NASA, is also an Earth Observation Satellite (EOS) that studies the water cycle but there's a special characteristic about it, which is its circular orbit, which means its eccentricity is zero; the Hubble Space Telescope and the International Space Station also classify as LEO satellites. Most LEO satellites have a period of approximately 100 minutes. The use

Table 2.1: LEO satellites examples. [4]

Satellite	Period (min)	Apogee (km)	Perigee (km)	Inclination (deg)
Aqua satellite	99	703	703	-98,20
PROBA-1	97	677	553	97,9
Hubble	95,47	541,4	537,4	28,47
ISS	92,65	408	401,1	51,64

of Signals of Opportunity in space related applications is still a subject being studied regarding feasibility for specific applications: since space debris detection[5] to orbit determination [6]. The most common type of signal of opportunity is Digital Terrestrial Television Signals due to their special characteristics mentioned in chapter 4, but a study regarding FM-B signals will also be performed in this thesis. In [7], a navigation problem in ambients where GPS is unavailable was presented, the solution was to use signals of opportunity and a Kalman filter to estimate the receiver location. A Software Defined Radio, a LNA and a regular laptop was the setup used to receive the signals, and the synchronization problem was solved by updating all the receiving laptops' internal clocks using an Internet server which provides an accuracy of a second, the results were good since the position error was around fifty meters.

Some other experiments have been done using cellphone network signals but these usually involve the receiver to also transmit [8], which is quite nonviable for this specific purpose, but nevertheless LTE and GSM signals may be used with correct methods of synchronization. For FM-B a method similar to multilateration will be used due to its analog nature. Multilateration enables passive geolocation and has already been implemented in aircraft using ADS-B signals, [9]using the time difference of arrival, this is the difference between the instant the signal is emitted to its reception, it is possible to compute distance since it travels at the speed of light. So by knowing the specific location of several groups of transmitters, with high power preferably, it is possible to extract an estimate of the satellite position.

TDoA applications have been used for many years since being introduced in the 1970's [10], in his work, the authors introduce a multilateration method for a spacecraft hovering at least five ground stations by using a TDoA approach[11]. But only later in [12], an actual solution to the geolocation problem presented in [11] is presented. Ho et. al. apply the method to a transmitter on the Earth surface and locate it using a set of geostationary satellite receivers.

For this thesis, a simplified perturbations model was needed in order to propagate TLEs of the satellite used for the study, in this case the PROBA-1. From the five models that exist: SGP, SGP4, SDP4, SGP8 and SDP8, the chosen one was SGP4 due to the fact that the author had already had contact with it in a Physics and Space Engineering course for a semester, while the other models would come with a steeper learning curve.

In [13], a graphic is presented where the number of transmitters, the distance of users and coverage area are illustrated. Also, Zheng et. al, refers that generally, wider bandwidth of signals, signals can resolve signals multipath and reflection in the city and indoor. The bandwidth for TV is from 6 MHz to 8 MHz according to standard. However, the bandwidth for GPS signal is 1 MHz. So TV signals can better resist multipath influence. In addition transmitters for TV presents different frequency for multichannel signals which offer more choices of signals for navigation. It is also noted that the difficulties in SoOP navigation application for complex low airspace flight can be overtaken by using a monitoring station for the signal synchronization. The transmitting time can be computed through monitoring SoOP transmitters. Then, the user obtains receiving time while the SoOP arrives. Therefore, the time difference of arrival can be computed through the difference between the receiving time and the transmitting time in the location server, which both the monitoring station and users communicate with.

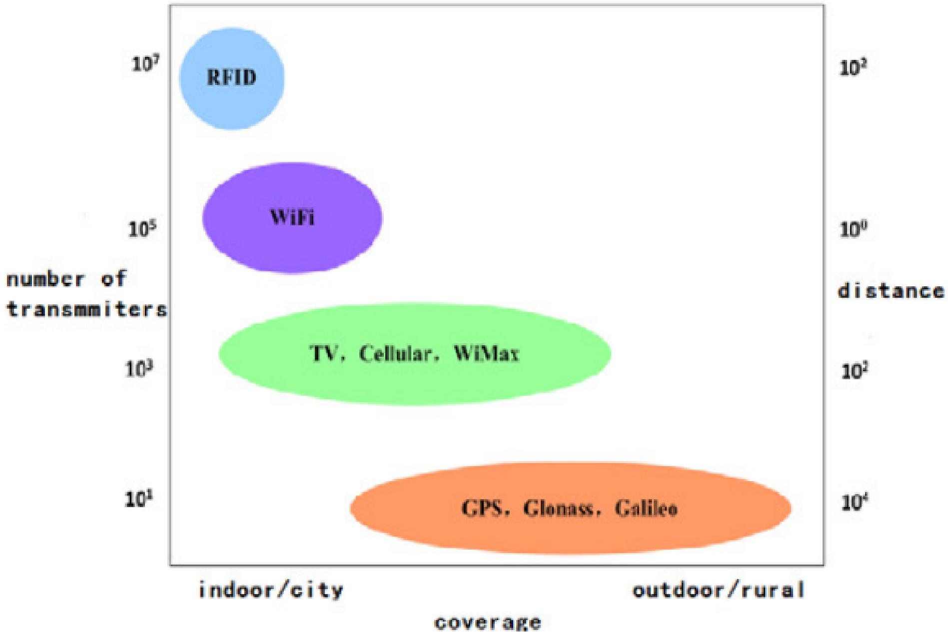

Figure 2.1: The number of transmitters, the distance of users and coverage for navigation signals [13]

Chapter 3

Relevant Orbital Dynamics

3.1 Kepler Parameters

Orbital parameters are required to uniquely identify a specific orbit. In celestial mechanics these parameters are generally considered in classical two-body systems where a Kepler orbit is used. The traditional orbital parameters are the six Keplerian elements[14]. The main two elements that define the shape and size of the ellipse:

- Eccentricity - associated with every conic section. It is a measure of how much the conic section deviates from being circular. In particular, the eccentricity of a circle is zero, the eccentricity of an ellipse which is not a circle is greater than zero but less than 1. The eccentricity of a parabola is 1 and of an hyperbola is greater than 1.

- Semimajor axis - For elliptical orbits, the semimajor axis is its longest diameter.

The two elements that define the orientation of the orbital plane are:

- Inclination - This parameter measures the tilt of an orbit around a celestial body, relative to the equator plane.

- Longitude of the ascending node - It's the angle from a reference direction, to the direction of the ascending node.

Finally the elements that define the orientation of the ellipse and the position of the body:

- Argument of periapsis - It defines the orientation of the ellipse in the orbital plane, as an angle measured from the ascending node to the periapsis.

- True anomaly - Parameter that defines the position of the orbiting body along the ellipse at a specific time-epoch.

A very important and helpful notion is that of two-line element set. It is a data format that encodes a list of orbital elements of an Earth-orbiting object for a given point in time. The data is fit into 70 columns of characters and does not include a trailing character. TLEs are simply the transmission format data rendered as ASCII text. Line number 2 gathers the information regarding the Kepler's parameters.

Table 3.1: TLE of PROBA-1.

1	26958U	01049B	18039.38927739	.00000687	00000-0	64798-4	0	9992	
2	26958	97.5977	3.6152	0071368	257.0670	102.2583	14.95190507886818		

3.1.1 Deviations and drift

A very important tool that helps visualizing orbits and their drift is the model SGP-4[15]. Using this asset and the respective TLE of PROBA-1[16], it was possible to compute the propagation of the orbit during thirty days. By plotting the satellite's position, it is possible to visualize the drift it is subject of, which will have to be accounted for when evaluating the transmission losses. This orbital decay results in a variation of the distance between the satellite and the Earth, resulting in uncertainties when calculating the transmission gains and losses, and it is caused mainly by the atmospheric drag, which is why the minimum distance for a satellite to perform a full translation around the Earth is 150 km.

Another aspect of interest regarding SGP-4 is its ability to compute position and velocity for any desired resolution of time, which allows for an evaluation of SNR evolution in relation to the distance to a transmitter. An aspect of most importance is of efficiency, the point is to minimize the number of observations per complete orbit of position and velocity.

Using PROBA-1 orbit as an example, a propagation of one day using a 10 minute step was made in order to obtain the error propagation vectors in the orbit referential - figure 3.1.

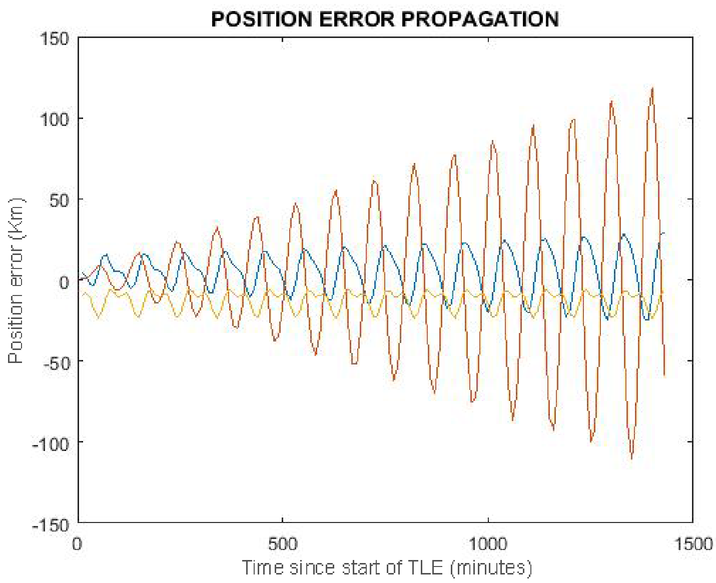

Figure 3.1: Position error propagation in three directions.

3.2 Relative Movement Description

Relative movement is very important to be understood and well characterized, because it is necessary for the implementation of the Kalman Filter. Here the relative movement is not between two different objects but the same one in different trajectories: a reference one, and a real one; but that is explained on chapter five. Regarding the mathematical model that correlates two movements and outputs this relation, it is very commonly used the Clohessy-Wiltshire equations model, which is deduced from the motion equations [14]. The Clohessy-Wiltshire matrices describe a simplified model of an orbital relative motion. From them, it is possible to obtain a closed form solution of the coupled Clohessy-Wiltshire differential equations in matrix form, allowing to find the position and velocity of the celestial body at any time given the initial position and velocity. Knowing that that $r(t)$ is the position and $v(t)$ the velocity and n is the mean motion and t the time:

$$\begin{bmatrix} r(t) \\ v(t) \end{bmatrix} = \begin{bmatrix} \Phi_{rr}(t) & \Phi_{rv}(t) \\ \Phi_{vr}(t) & \Phi_{vv}(t) \end{bmatrix} \begin{bmatrix} r(0) \\ v(0) \end{bmatrix}$$

$$[\Phi_{rr}(t)] = \begin{bmatrix} 4-3cos(nt) & 0 & 0 \\ 6(sin(nt)-nt) & 1 & 0 \\ 0 & 0 & cos(nt) \end{bmatrix}$$

$$[\Phi_{rv}(t)] = \begin{bmatrix} \frac{1}{n}sin(nt) & \frac{2}{n}(1-cos(nt)) & 0 \\ \frac{2}{n}(cos(nt)-1) & \frac{4}{n}sin(nt)-\frac{3}{n}nt & 0 \\ 0 & 0 & \frac{1}{n}sin(nt) \end{bmatrix}$$

$$[\Phi_{vr}(t)] = \begin{bmatrix} 3n\cdot sin(nt) & 0 & 0 \\ 6n(cos(nt)-1) & 0 & 0 \\ 0 & 0 & -n\cdot sin(nt) \end{bmatrix}$$

$$[\Phi_{vv}(t)] = \begin{bmatrix} cos(nt) & 2sin(nt) & 0 \\ -2sin(nt) & -3+4cos(nt) & 0 \\ 0 & 0 & cos(nt) \end{bmatrix}$$

Since these matrices are invertible, they can also be solved for the initial conditions given only the final conditions and the properties of the target vehicle's orbit.

3.3 Error evolution for reference trajectory

When propagating a single trajectory using only one TLE, the real trajectory tends to get farther and farther away creating an error. For a better approximation of a real trajectory, multiple TLEs were used to propagate in order to decrease this error, as shown on 3.2.

These TLEs, which were taken from Space-Track [17], when propagated do not take the natural drift the satellite is prone to into account. The error in relative coordinates is plotted on 3.3. For

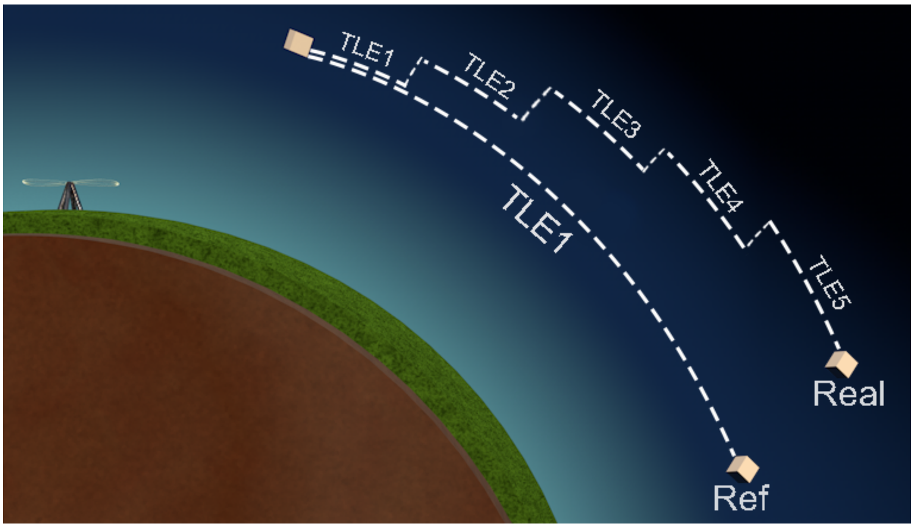

Figure 3.2: Comparison of Real and Reference Trajectories.

3365 minutes, the error evolves till 150 km which is substantial, meaning that every minute, they drift around 45 meters. This result was verified using Orbitron (3.4) by taking elevation, azimuth and range values for the same site, using TLE1 and TLE5 (referring to 3.2). It is important to refer that this formulation with the five against one propagation of TLEs was merely used as an example for study used in this thesis.

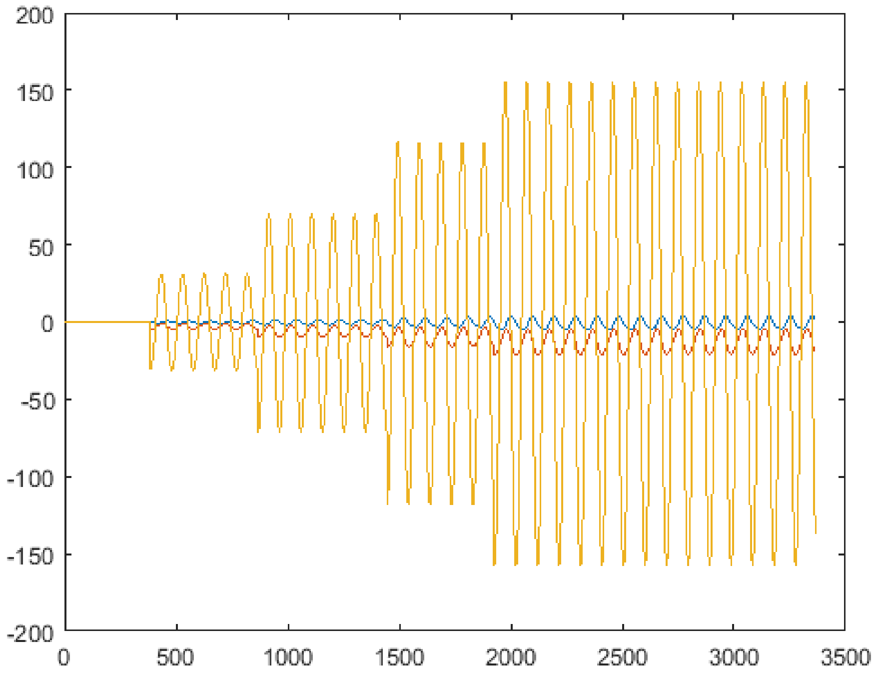

Figure 3.3: Difference between real and reference in relative coordinates evolution in time.

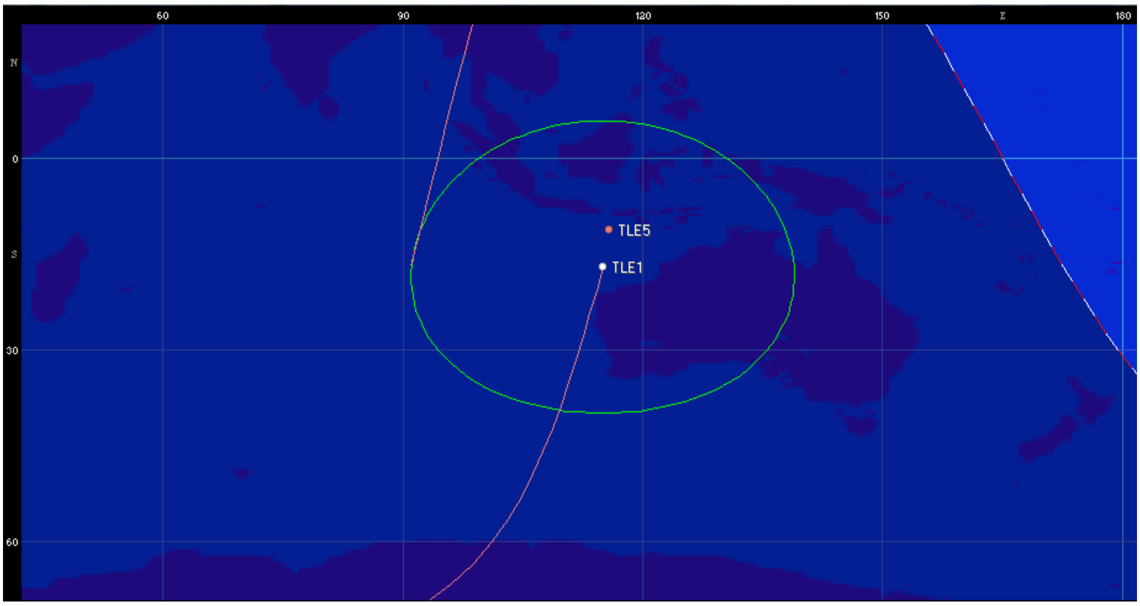

Figure 3.4: Orbitron screen showing the difference between the real trajectory and the reference one.

Chapter 4

Feasibility Study

4.1 Signals of Opportunity

Signals of opportunity have been a field where the author has been involved since 2015 when an application in the programme BEXUS [18] was accepted. The experiment was SIGNON: signals of opportunity for navigation. The goal of SIGNON experiment was to use radio signals of opportunity, such as FM broadcast stations, DTTV stations and ADS-B signals transmitted by passing aircraft, to obtain navigation information during a stratospheric BEXUS flight. For this purpose software defined radio (SDR) receivers, tuned to these signals of opportunity, were used. Post-processing by correlation with equivalent data gathered by a small set of reference stations in known locations are Sweden and Finland allowed for computing distances between transmitting stations and the balloon and, consequently, obtain the balloon trajectory. Comparison with GPS data provided an assessment on feasibility and accuracy for the use of these signals of opportunity for navigation at high altitude and for LEO satellites. The SIGNON experiment also tested the possibility of using DTTV signals for passive radar applications, measuring the signals scattered by the surrounding environment together with the direct signal from the transmitting stations. Combination of such measurements along the flight trajectory would enable to produce a scattering map of the vicinity of the flight trajectory. Unfortunately the quality of the signals and the flight weren't ideal and, as such, it wasn't possible to take conclusive information about the feasibility of using these signals for navigation but it was proven that it was possible to receive the signals and that, with better conditions, it would most probably be possible to compute the position of the satellite with enough quality, nor it was possible to elaborate a good enough scattering map.

After BEXUS, the study around SoOP continued in REXUS with the SPAN experiment: the main objective of the SPAN experiment was also to use signals of opportunity to navigate, integrating timing information extracted from the signals to obtain the relative position from a known starting point. In this specific case, the team would use DTTV, GSM and LTE signals. These signals would be slaved to a precise atomic clock on transmission, having significant power and bandwidth and transmitted continuously or never too long without being transmitted. Using a SDR and an on-board Rubidium Atomic Clock in a rocket module would allow for the reception of the signal and couple it with the synchronized signal given by a timing signal generator that will be calibrated with the clock. Extracting the delay between a received symbol and the timing marker generated by the SPAN experiment, it would be possible to calculate the relative distance between the transmitter and the receiver. Knowing the start position, the evolution of this delay gives the trajectory taken by the REXUS rocket. The ultimate goal of SPAN was to develop a compact methodology for future LEO satellites navigation, possibly tightly integrated with communications.

The next step was to start studying the feasibility of using signals of opportunity for navigation with real Low Earth Orbit satellite data which is the main objective of this thesis.

4.2 Signals Evaluation

A concept that is important to introduce is that of signals of opportunity. Being primarily used for other purposes, such signals are, by their availability and their characteristics, suitable for performing measurements just by being received. It is an objective to use certain broadcasted signals for Low Earth Orbit (LEO) satellites navigation, establishing a navigation system similar to GPS, that can be used in flight from low to very high altitudes, including possible use on LEO satellites.

4.2.1 DTTV

DTTV (Digital Terrestrial Television, 750Mhz to 758Mhz in Portugal) signals exhibit a constant average power spectrum along their bandwidth. This spectrally suitable for correlation. Being digitally coded with forward error correction data included enables reconstruction of the originally transmitted signals. Consequently, correlation between the received signals with the digitally reconstructed ones allows for accurately detecting the transmitter correlation peaks.

The accuracy gotten from the signal is a decisive factor, and it should be around the tens of meters. The resolution is obtained using:

$$\frac{Velocity\ of\ light}{Bandwidth} \tag{4.1}$$

The bandwidth definition that is used in calculations refers to the frequency range in which the signal spectral density is nonzero or above a small threshold value. The threshold value is often defined relative to the maximum value, and is most commonly 3dB point.

Knowing the DTTV signal bandwidth is 8 MHz, then the resolution would be:

$$\frac{3 \times 10^8}{8 \times 10^6} = 37,5\ m \tag{4.2}$$

If the recorded signal has good SNR, it is possible to compute the correlation peak instant with subsample accuracy, so the resolution can be improved ten times or even more.

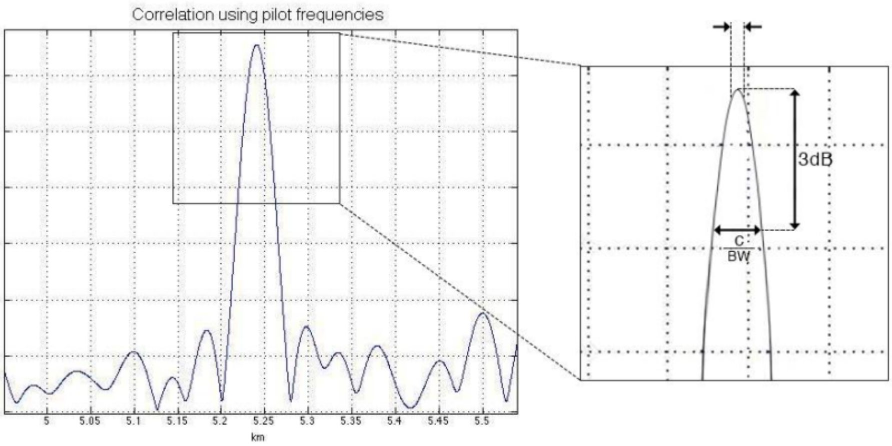

Figure 4.1: Correlation Peak.

The average power of DTTV signal transmitters in Portugal is around $1000W$, which is equivalent to $60dBm$. [19] In order to evaluate the quality of a signal and decide on its feasibility of use, it is necessary to compute a link budget and analyze the final SNR. The free-space path loss attenuation, which can be derived from the Friis formula[20]:

$$\left(\frac{\lambda}{4\pi L_1}\right)^2 \tag{4.3}$$

$$\lambda = \frac{c}{f} \tag{4.4}$$

Where:

- λ=wavelength;
- d=distance between the transmitter and the receiver, for a satellite it must be the apogee, the worst scenario;
- c=speed of light;
- f=frequency.

Considering PROBA-1 as the example, the average transmitter power 1000W EIRP, and the frequency 750 MHz:

$$FSPL(dB) = 20log\left(\frac{\frac{3\times10^8}{750\times10^6}}{4\pi \times L_1 \times 10^3}\right) \tag{4.5}$$

The antenna gain can be computed the integral along the whole antenna length L:

$$E = \int_{-L/2}^{L/2} e^{-j2\pi\frac{xsin(\theta)}{\lambda}}dx = j \cdot sinc\left(\frac{L}{\lambda}sin(\theta))\right) \tag{4.6}$$

The ratio between the antenna length and the wavelength influence the gain of the antenna and consequently the *RX*, the antenna gain can be given by:

$$G = 20log(sinc(\frac{L}{\lambda}sin(\theta))) \tag{4.7}$$

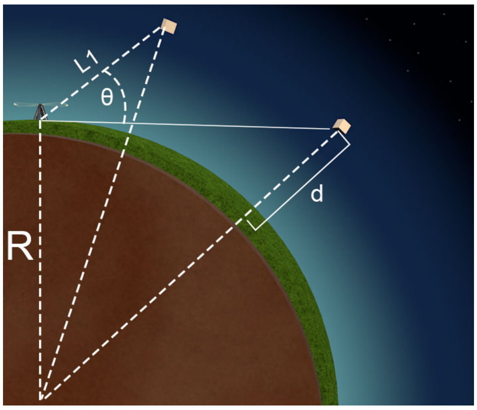

Figure 4.2: Visualization of the triangle problem.

As the angle the satellite does with the Earth's surface tangent decreases, it will go farther from the antenna but directivity will be better, increasing the gain. So, in order to find the maximum gain for reception, an analysis considering all values for the angle and distance must be done, as depicted in figure 4.2.

By the law of cosines:

$$(R+d)^2 = R^2 + L_1^2 - 2 \cdot L_1 \cdot R \cdot \cos\left(\theta + \frac{\pi}{2}\right) \tag{4.8}$$

- R=6371 km;
- d=677km.

The reception total power is:

$$RX = TX + FSPL + G \tag{4.9}$$

After running a script that solves the equation 4.8 for $\theta \in [0; \frac{\pi}{2}]$ and computing the $FSPL$ and G for each value of θ and L_1, RX was then calculated and found its maximum. The value of θ for which RX is maximum for a $\frac{L}{\lambda}$equal to one, this is, antenna length equal to the wavelength was 25.2^o, the computed gain values are in table 4.1 and the value of RX for different values of $L1$ is presented in 4.3, the horizontal line represents the value of RX that produces a SNR of 10 dB, considered to be the minimum for the purpose.

The noise on the transmission is:

$$N = 10log(k \times BW \times T0) \tag{4.10}$$

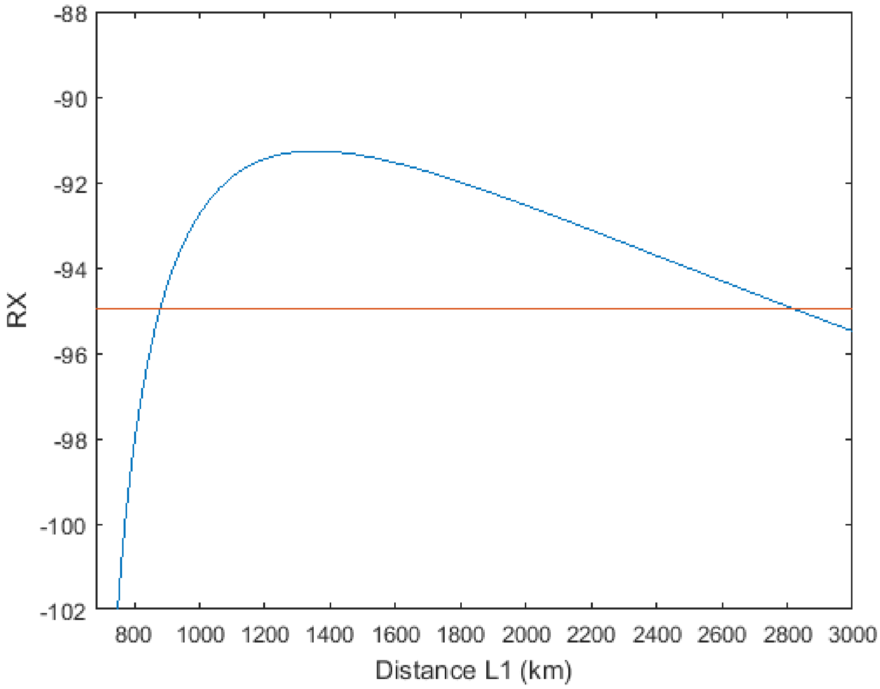

Figure 4.3: RX for different L1 values.

- k=1.379 $\times 10^{-23}$ $m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$;
- BW=8MHz;
- $T0$=290K.

$$N = -104,9495dB \tag{4.11}$$

Considering a noise figure at the reception of 2dB and a gain of 4dB for the reception antenna:

$$SNR = -91,27 - (-104,95) - 2 + 4 = 13,68dB \tag{4.12}$$

But actually, the window of values of θ for which the SNR is acceptable is not, by any means, restricted to the optimal value of θ as seen on 4.3. For different values of distance $L1$ there are many values of theta that make the purpose.

Figure 4.3 illustrates very well how wide is the gamma of distances for which the gain is high enough for the SNR to be higher than ten. It is worth noticing that for values of θ below zero, the Earth surface block the signal route, explaining the sudden gain drop for larger distances presented in the graphic. Concluding, DTTV signals present themselves as a good candidate for this purpose due to their structure and ease of synchronization.

Table 4.1: Computed gain values for the best value of θ.

θ	L_1	TX	$FSPL$	G	RX
25.2º	1342,366 km	60 dBm	-152,50dB	1,235 dB	-91,2654 dBm

4.2.2 FM-B

FM-B (Frequency Modulation Broadcasting, 87,5MHz to 108Mhz) are used in radio communication and commercial radio. Similarly to DTTV, FM-B signals are particularly interesting because the ground stations transmit them continuously with significant power, for example: "Antena 1" transmits with 100 kW in Porto and Lisboa [21], reaching long distances with enough signal to noise ratio (SNR) to enable decoding them. But, contrarily to DTTV, these are analog signals, which means the processing that allows for later synchronism will be harder, only by comparison with further information from ground stations will it be possible to decode the original signal. But despite that, the availability of FM-B signals is very high, which is very advantageous.

FM-B signals exhibit a low bandwidth and high transmission power, so they reach the largest distances. Although considered low when compared to the other signals, their spectrum span is about 100 kHz, which provides correlation accuracy in the order of hundreds of meters.

A Link Budget for FM signals is generous due to their higher power and lower bandwidth, it is a certainty that they would be received with more than sufficient SNR, being the only issue the necessity of knowing *a priori* the location of a set of, at least, three ground stations at a time.

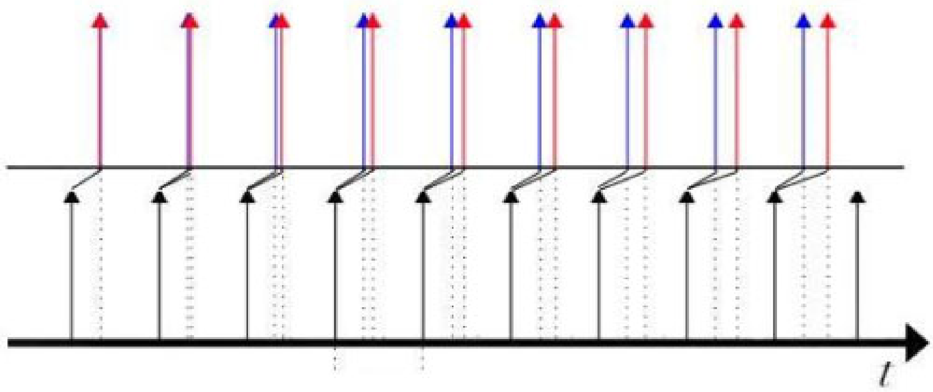

Figure 4.4: Delays comparison.

In order to correctly associate the received signal with the transmitted one, it is necessary to have a reference with a known specific clock. Injecting timestamps to the signal would be a possibility be the original signal was known, but due to its analog nature, this not possible. Coupling the original signal with a reference signal will allow for a correct correlation, to correlate the evolution of the delays between the expected location for the correlation peak and its actual position will allow for estimating distance, as illustrated in figure ??. This reference signal should be transmitted by a strategically placed ground station that would receive the signal with excellent SNR, and transmit only specific portions of that signal that contain information that would serve as signature. This delays should also be studied in comparison with the satellite orbit characteristics and its potential drift.

4.3 Link Budget as a function of distance to the transmitter

In the previous point, reception power in function of the distance to the transmitter has already been computed - figure 4.3. In this section, the objective was to compute the SNR resultant of a transmission for a satellite with orbit altitude $d \in [200km; 800km]$ in function of d. This was made in order to completely study the SNR variation and posteriorly pick a set of orbits that better fit the purpose, a Matlab script was written for that effect. This script solves iteratively the second degree equation 4.8 and for each value of d, with a step of 50 km, calculates the better SNR for a specific θ to make sure that there is at least one value of θ that produces a good enough SNR. Plotted in figure 4.5 are the values of SNR as a function of d for the optimal value of θ. By analyzing the results it is possible to verify that the lower the altitude the higher the SNR and it varies in an almost linear way. When d is equal to 200 km, the SNR is 23,4 dB; when d is 800 km, the SNR is 12,4 dB.

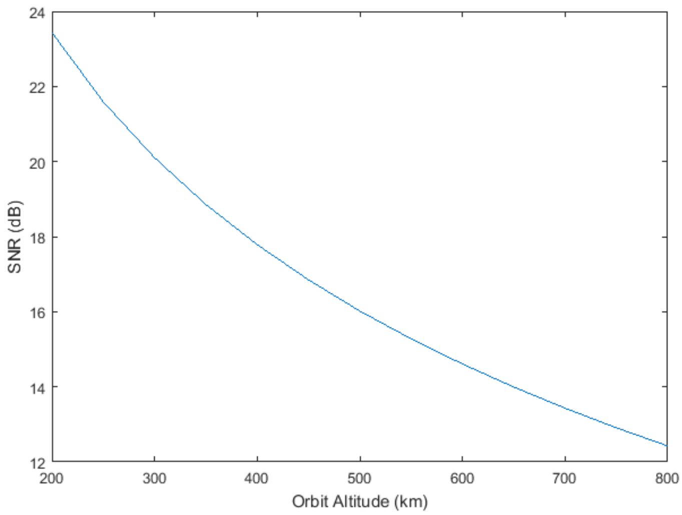

Figure 4.5: SNR as a function of orbit altitude d.

4.4 Research regarding availability of stations with the desired specifications

The most important characteristics to look out for when picking a set of stations, would be the transmission in a Multi-Frequency Network (MFN) and high power transmissions. MFN is a valuable aspect because it facilitates the differentiation of signals allowing for the identification of the signal in study. Power is also important because the higher the power, the better the signal reception. Regarding world availability, most central Europe countries such as Germany, France, Portugal, Italy and Benelux use Single Frequency Network [22], and due to their relative small area, they're not particularly interesting for the purpose, eliminating this zone's transmitters from the set to pick; Africa is also an area where there are few transmitters to choose from, since countries are mostly still in the process of, or have not even started, switching from analog to digital television.

A global broad coverage is of interest, therefore the stations to be picked should be spread along the largest possible area. The United States of America are a very interesting country to pick stations from for many reasons: there is a very extensive network of DTTV transmitters more or less homogeneously spread along its total area which is relatively big, also they have a very complete database with information about every transmitter provided by the Federal Communications Commission [23].

Australia has similar qualities to the USA and, despite having some small SFNs, if the chosen stations transmit in different frequencies there should not be any issues.

Stations were selected in pairs so that the chosen pair in each iteration of the loop would be distanced not more than 500 km. A complete list of the selected stations is presented in table 4.2 with the respective latitude, longitude and power of emission.

Table 4.2: Selected stations.

	Location	Latitude	Longitude	Power
USA	Portland 1	43.924722	-70.490833	1000 kW
	Portland 2	43.851778	-70.327333	1000 kW
	Denver 1	39.728361	-105.237694	1000 kW
	Denver 2	39.730722	-105.232111	1000 kW
	Washington DC	38.956111	-77.082778	1000 kW
	Washington DC 2	38.950278	-77.079444	500 kW
	Miami 1	25.968889	-80.221944	1000 kW
	Miami 2	25.958611	-80.211944	1000 kW
	Atlanta 1	33.807333	-84.339306	1000 kW
	Atlanta 2	33.797611	-84.333806	1000 kW
	Chicago 1	41.878889	-87.635556	475 kW
	Chicago 2	41.878917	-87.636167	350 kW
	New Orleans 1	29.920306	-90.024583	300 kW
	New Orleans 2	29.954139	-89.949528	300 kW
	Boston 1	42.310278	-71.236667	825 kW
	Boston 2	42.302972	-71.218028	825 kW
	Oakland	39.403972	-79.293361	100 kW
AUS	Mount Canoblas	-33.34222222	148.98361111	350 kW
	Mount Sugarloaf	-32.89194444	151.53833333	250 kW
BR	Rio de Janeiro	-22.94975	-43.22939	100 kW
	São Paulo	-23.55472	-46.66444	363 kW
FIN	Kuopio	62.73888	27.54250	50 kW
	Pyhävuori	62.28694	21.64166	50 kW

Chapter 5

Navigation Problem Formulation

5.1 Kalman Filter

5.1.1 Introduction

The Kalman filter [24] has been accepted as an optimal form of solving problems regarding prediction and estimation tasks, being used in a wide spectrum of scientific areas, from robotics to space. The main objective of filtering is to only extract the desired information from a signal, ignoring everything else. The state of the system is a set of variables that characterize the evolution of the system. Usually a mathematic model represents the dynamic evolution and enables one to compare the entries and outs of the system. How well a filter performs the desired task can be analyzed with a cost or loss function. The main goal of the Kalman filter is to minimize the loss function.

5.1.2 Implementation

The main factors that influence how much feasible is using SoO are how many stations would be needed and how high the observation rate would need to be, this can be simulated using a Kalman Filter for the satellite position and velocity estimation, with a reference trajectory given by the propagation of a single TLE and a pseudo-real trajectory which is achieved propagating multiple TLE with a total duration and origin equal to the reference one, like presented on 3.2. An effort regarding synchronization was made after issues with the gathering of the five TLEs because the start of one much coincide exactly with the minute after the ending of the preceding one. In order to achieve this, the propagation of the TLEs was made iteratively for a relative time computed with the start days taken from each of the TLEs.

Also, in order to compute the distances between stations and a satellite, a Matlab script was made that receives latitude, longitude and altitude coordinates of two stations and the real and reference trajectories of the satellite in ECI coordinates, which are given by the SGP4 model, and converts all coordinates to ECEF in order to have every position in the same frame and be able to compute vectors to achieve distances α, β and γ and build the matrix C of the Kalman Filter.

These three relative distances are obtained by subtracting both vectors that with directions between the satellite and the pair of stations being observed at the moment. Following image 5.1 notation, α, β and γ are the three components of $\vec{u}3$.

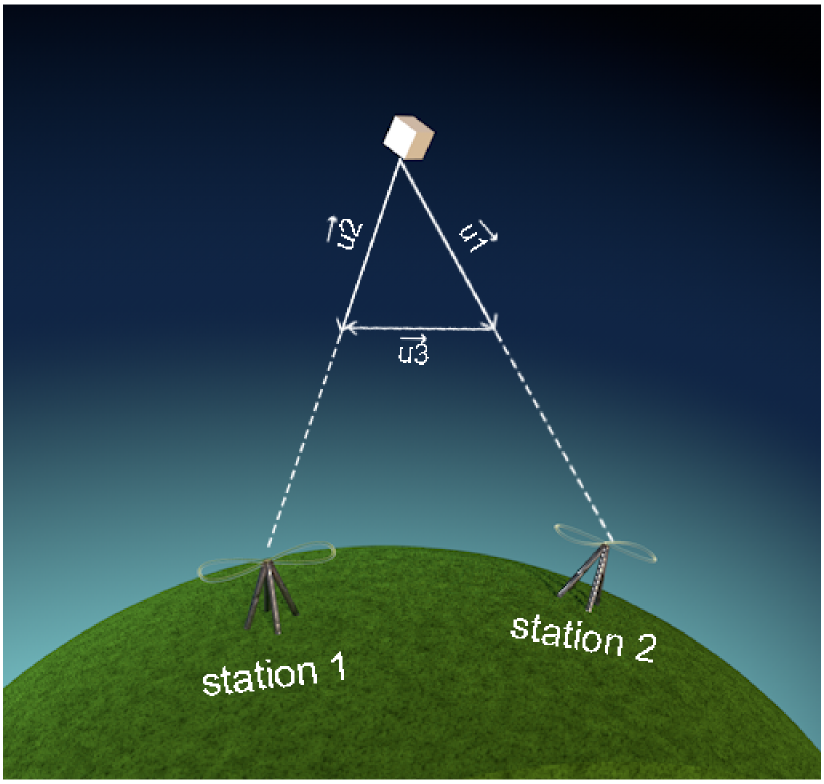

Figure 5.1: Vector representation.

The state matrix A is made employing the Clohessy-Wiltshire equations and is constant throughout the whole filter process, B only applies noise to the velocities because the position varies with the velocity, C contains the distances α, β and γ and has as many lines as observations. n being the mean motion of the satellite, that is taken directly from the TLE and converted from revolutions per day to radians per minute, and t the time interval between observations which in this case is one minute :

$$A = \begin{bmatrix} 4-3cos(nt) & 0 & 0 & \frac{1}{n}sin(nt) & \frac{2}{n}(1-cos(nt)) & 0 \\ 6(sin(nt)-nt) & 1 & 0 & \frac{2}{n}(cos(nt)-1) & \frac{4}{n}sin(nt)-\frac{3}{n}nt & 0 \\ 0 & 0 & cos(nt) & 0 & 0 & \frac{1}{n}sin(nt) \\ 3n\cdot sin(nt) & 0 & 0 & cos(nt) & 2sin(nt) & 0 \\ 6n(cos(nt)-1) & 0 & 0 & -2sin(nt) & -3+4cos(nt) & 0 \\ 0 & 0 & -n\cdot sin(nt) & 0 & 0 & cos(nt) \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad C = \begin{bmatrix} \alpha & \beta & \gamma & 0 & 0 & 0 \end{bmatrix} \qquad D = \begin{bmatrix} 1 \end{bmatrix}$$

The step of the filter is one minute, which is the same as the one used for the propagation of the TLE, and for each step, a script compares the current position of the satellite with the dataset of stations that contains, for each one, the respective azimuth, elevation and range. This script returns, if there are at least two stations with more than 15^o of elevation relative to the satellite's position, the coordinates of the pair of stations with the highest elevation, in ECEF. These coordinates are used in each iteration to compute relative distances between the real position of the satellite and each station, and the difference between these two distances is used as the real measurement component in the Kalman Filter.

The model equations are:

$$yreal_k = \|traj_{real} - station_2\| - \|traj_{real} - station_1\| + v \tag{5.1}$$

$$yestimated_k = \left\|traj_{reference} + traj_{estimated} - station_2\right\| - \left\|traj_{reference} + traj_{estimated} - station_1\right\| \tag{5.2}$$

$$K_k = P_k' + C^T \left(CP_k'C^T + R\right)^{-1} \tag{5.3}$$

$$\hat{x}_k = \hat{x}_k + K_k\left(yreal_k - yestimated_k\right) \tag{5.4}$$

$$P_k = (I - K_kC)P_k'(I - K_kC)^T + K_kRK_k^T \tag{5.5}$$

Both 5.4 and 5.5 are only computed when the condition of at least two stations having an elevation higher than 30^o is verified.

$$\hat{x}_{k+1} = A \cdot \hat{x}_k \tag{5.6}$$

$$P_{k+1} = AP_kA^T + Q \tag{5.7}$$

- $\hat{x}$ = state vector.
- P = Covariance Matrix.
- w and v = noises.
- K = Kalman gain.

v is the process noise and is around tens of meters, while w is the dynamic noise and is closer to one meter.

The state vector can be described as the offset between the real trajectory and the reference one in relative coordinates ijk and thus, its error can be calculated by comparing with with difference between the real and reference trajectories in ECEF converted to a ijk referential. This difference tends to increase in intervals that coincide with the change of TLE, and after 3500 minutes, it is around a hundred and fifty kilometers, as shown on figure 3.3. This drift distance has been verified using the application Orbitron by verifying the elevation and azimuth of the first TLE and the fifth TLE in the same instant of time for the same observation point and computing distance.. This conversion is done using a transformation matrix formed with unit vectors resultant of the comparison of the two trajectories.

The state vector, depending on the number of stations seen with an elevation above thirty degrees which allows for a new observation, is more or less similar to 3.3 , as already seen in the previous chapter. For 2500 stations the approximation is good, the plot of the state vector is seen on 5.2.

The error of the approximation can be seen in 5.3. For 2500 stations in can be verified that the error decreases when there are observations and tend to be around one kilometer after around 2000 minutes, which for the satellite in question is around twenty-two complete revolutions. In order to better analyze how much the quantity of stations influence the time the error takes to converge, other simulations with less stations were made after this one.

It is visible that with only 120 stations distributed equally by the six zones chosen, so twenty per zone: USA, Brazil, Europe, Russia, China and Australia, 5.4, the time it takes much more time to converge, around ten more revolutions, but eventually it gets to a point where the error is plausible.

It was verified that using more than 2500 stations, the difference is not very significant, which proves that the quality of the simulation saturates around 2500 stations, and using more is obsolete.

Another test using 24 stations, six per zone was made, to assess if it would, like with 120, eventually get to an acceptable point, even if it would take more time. 5.5 is this error evolution in

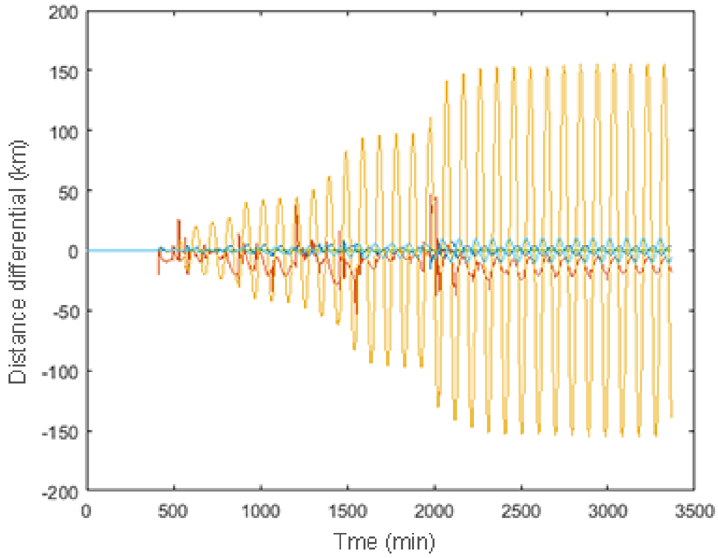

Figure 5.2: State Vector’s evolution with time.

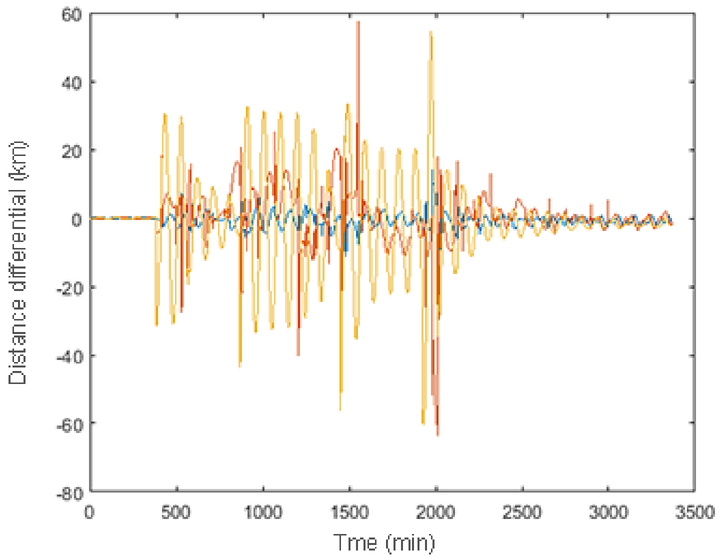

Figure 5.3: Error evolution with time using 2500 stations .

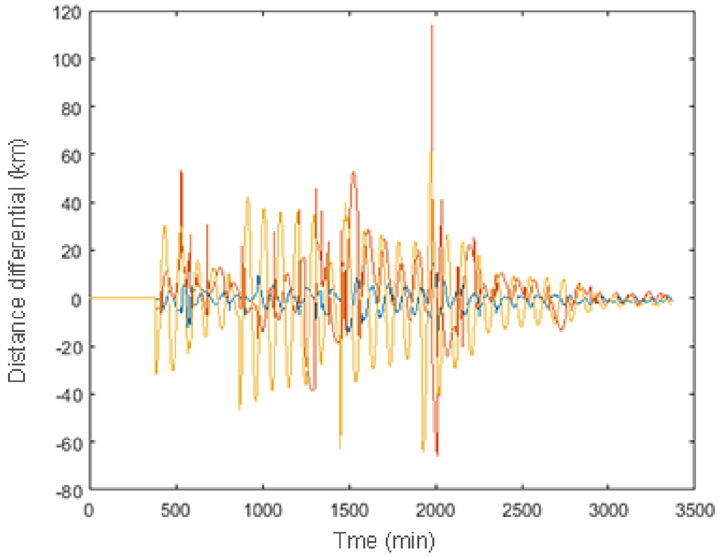

Figure 5.4: Error using 120 stations evolution with time.

Table 5.1: Full percentages of 2500 random stations.

USA	Brazil	Europe	Russia	China	Australia
750	250	500	500	250	250

function of time, and, because the number of observations is so low, it does not behave minimally in a controlled way and does not only, not converge, but actually increases and decreases with no rule whatsoever.

5.2 Error in function of number of stations analysis

Despite having chosen a set of real stations, it turned out very difficult to get information on stations globally and in sufficient quantity to test different scenarios. The thought solution was to generate varying quantities of random locations quantities inside bounded specific areas and analyze the error for each set of locations. The implementation was running a "for" cycle from 0.01 to 1 in increments of 0.01 corresponding to the percentage of stations used in each boundary, knowing that the full quantities are in table 5.1, and the plot of the two thousand and five hundred stations in figure 5.6.

In each iteration of this loop the average error of the state vector was calculated and stored in an array. The plot of this array of errors in function of the number of stations gives information about the amount of stations that are sufficient to achieve a sufficiently low error.
The results of the analysis of the error in relation to the quantity of stations can be seen in figure 5.7. It can be seen that the error is less than one kilometer to almost every amount of stations.

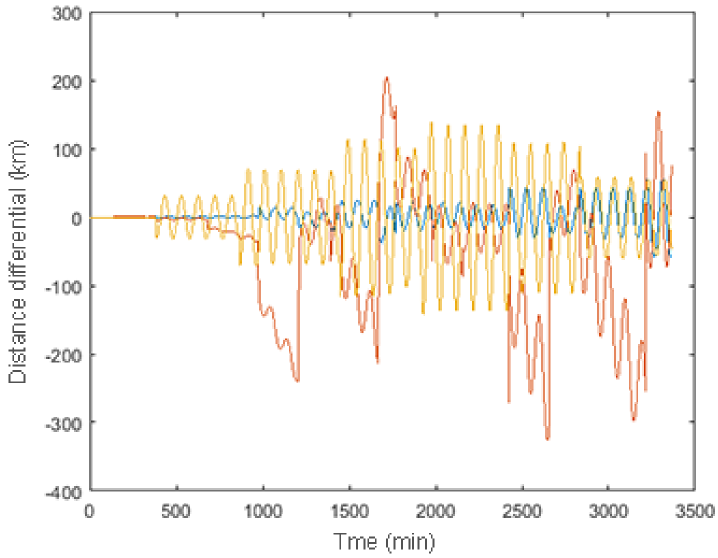

Figure 5.5: Error using 24 stations evolution with time.

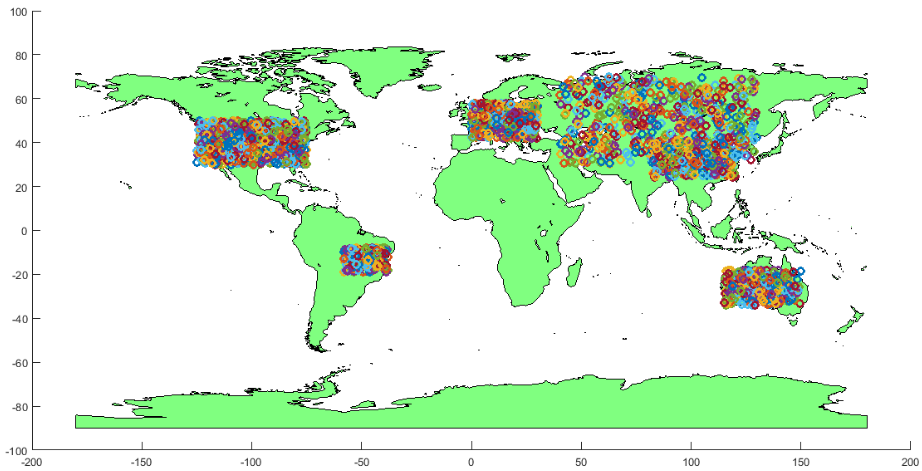

Figure 5.6: Placement of 2500 stations across the land part of the Earth where usable transmitters are most likely to exist .

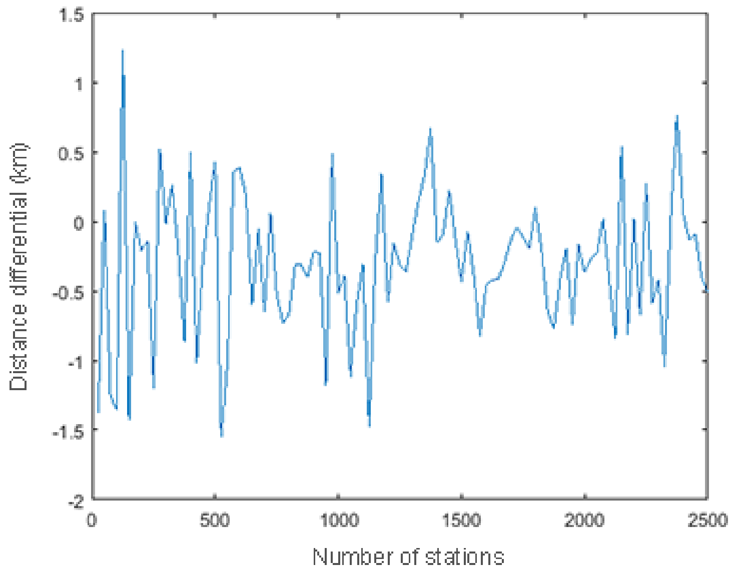

Figure 5.7: Norm of the three components of the error means in kilometers in function of the number of stations.

In order to better study the error evolution, another simulation was made but with the maximum number of stations as six hundred: a hundred to each zone (USA, Brazil, Europe, Russia, China and Australia).

As it can be seen in figure 5.8 , with few stations the error is very high but rapidly it stabilizes.

Another test using just the hundred stations placed on USA territory was made in order to verify if that provides enough observations for the Kalman Filter, 5.9. The error stabilizes just around ten kilometers which is quite large for a position error, which lets one conclude that choosing stations spread across the largest area possible covered by the satellite is an aspect of most importance. And the desired total number of stations used for this purpose should be around one thousand stations.

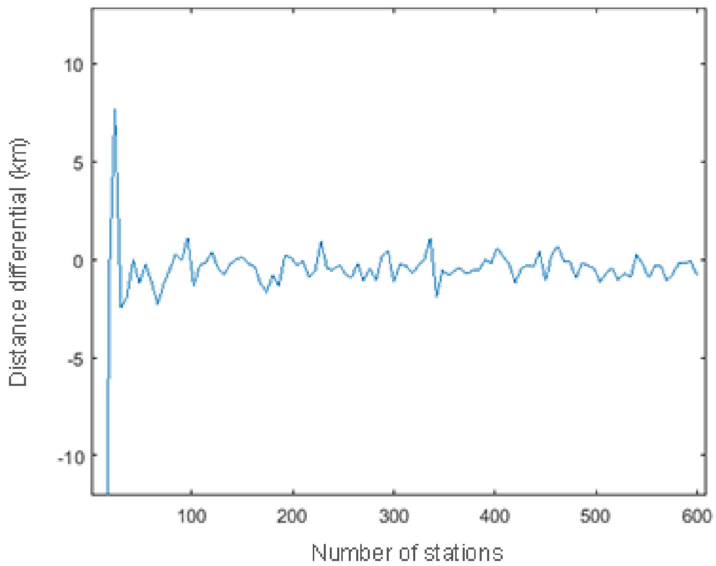

Figure 5.8: Norm of the three components of the error in kilometers for a maximum of six hundred stations.

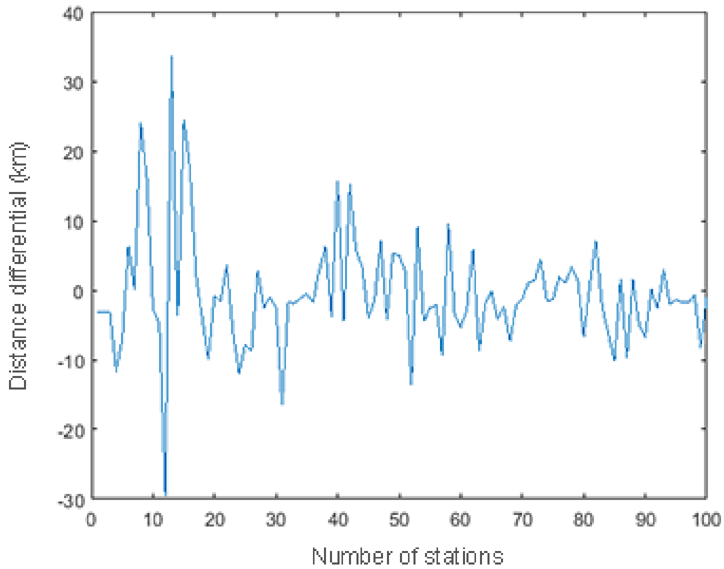

Figure 5.9: Norm of the three components of the error in kilometers for just a hundred stations placed only on USA territory.

Chapter 6

Final Remarks

This study clearly shows that from the availability point of view, it is possible to navigate in LEO using signals of opportunity. This is also corroborated by the experience the author has had with educational programmes organized by multiple European space agencies which allowed for a great deal of contact with the entire space environment that triggered an interest by the author in this area of research, the author's area of formation is in Electrical and Computer Engineering. Because of this fact, there was quite a large amount of time spent getting used and understanding concepts that are essential and basic in the Space Engineering field, such as understanding coordinate frames and how to convert from one another. Additionally programming bugs using the SGP4 model and integrating with the Kalman Filter with time rigor were appearing frequently and to solve them was very important, which took a large portion of the available time.

If there was more time available, this study would proceed with assessing more signals and their feasibility, as was intended previously, such as LTE and FM-B or even GSM. Also, an intensive debug regarding coordinate frames conversions, which sometimes are prone to confusion and the smallest mistake invalidates the entirety of the results, should be done. An implementation in a small footprint computer would be very important in order to open up possibilities of using this system in small size satellites as for example Cubesats to estimate the error evolution and perform maneuvers and take decisions autonomously based upon that; and for that, a conversion from Matlab to C would be performed.

The results were very satisfactory and promising since not only the number of stations necessary that was concluded in chapter five is realistic, but the error tends to be around one kilometer with some quickness which is extremely plausible and increases the interest the implementing it in a real time system. So the scenario after performing this feasibility study looks promising and hopefully opens doors regarding navigation with signals of opportunity.

Bibliography

[1] E. Patiño Rodriguez J. van den Ijssel, P. Visser. Champ precise orbit determination using gps data. Technical report.

[2] Current situation with cocom regulations and gps receivers for balloons and cubesats - space exploration stack exchange. https://space.stackexchange.com/questions/14687/current-situation-with-cocom-regulations-and-gps-receivers-for-balloons-and

[3] Paul A Cross Robert J Mason Joseph H Harrison Toby A Webb, Paul D Groves. A new differential positioning method using modulation correlation of signals of opportunity - ieee conference publication. http://ieeexplore.ieee.org/document/5507270/.

[4] Office of Safety and Mission Assurance. Nasa safety standard 1740.14, guidelines and assessment procedures for limiting orbital debris, 1995.

[5] Patrycja Szewczak Marek Kubel-Grabau Martyna Zaborowska Urszula Zielińska Jakub Kopyciński Paulina Woźniak Agnieszka Borucka Gabriela Moryc Wioleta Rzęsa Bartłomiej Majerski Viktor Szabó Dorota Mieczkowska, Jakub Wójcicki. Detection of objects on leo using signals of opportunity - ieee conference publication. http://ieeexplore.ieee.org/document/8053660/.

[6] Marcus J. Holzinger Johnny L. Worthy III. Uncued satellite initial orbit determination using signals of opportunity. http://www.ssdl.gatech.edu/sites/default/files/papers/conferencePapers/AAS-15-738.pdf.

[7] Chong Meng Samson See François Quitin Chi Cheng Mei Leng, Sirajudeen Gulam Razul and Wee Peng Tay. Joint navigation and synchronization using soop in gps-denied environments: Algorithm and empirical study.

[8] K. A. Fisher. Enhanced 911: Emergency location and indoor global position system.

[9] S. Rau W. Konle R. Kaune, C. Steffes and J. Pagel. Wide area multilateration using ads-b transponder signals - ieee conference publication. Information Fusion (FUSION), 2012 15th International Conference on, 2012.

[10] P. R. Escobal. 3-d multilateration: A precision geodetic measurement system. Technical report, March 1973.

[11] K. M. Ong P. R. Escobal and O. V. Roos. Range difference multilateration for obtaining precision geodetic and trajectory measurements. Technical report.

[12] K. Ho and Y. Chan. Solution and performance analysis of geolocation by tdoa. Technical report.

[13] L. Zheng and R. Xue. Signals of opportunity navigation methods for complex lower airspace flight. In *2011 IEEE 5th International Conference on Cybernetics and Intelligent Systems (CIS)*, pages 272–276, Sept 2011. doi:10.1109/ICCIS.2011.6070340.

[14] Howard Curtis. *Orbital Mechanics for Engineering Students*. Elsevier, 2004.

[15] David Vallado. *Fundamentals of astrodynamics and applications*. Springer, 2007.

[16] www.tle.info/data/engineering.txt. http://www.tle.info/data/engineering.txt.

[17] Space-track.org. https://www.space-track.org.

[18] Rexus/bexus. http://rexusbexus.net/.

[19] Anacom - rede de frequência única - canal 56. https://www.anacom.pt/render.jsp?contentId=1021427.

[20] Small satellite link budget calculation. https://www.itu.int/en/ITU-R/space/workshops/2016-small-sat/Documents/Link_budget_uvigo.pdf.

[21] Anacom - antena 1 - continente. https://www.anacom.pt/render.jsp?contentId=62263.

[22] EUROPEAN BROADCASTING UNION. Benefits and limitations of single frequency networks (sfn) for dtt. https://tech.ebu.ch/docs/techreports/tr016.pdf, 2002.

[23] Tv query broadcast station search | federal communications commission. https://www.fcc.gov/media/television/tv-query.

[24] R. E. Kalman. A new approach to linear filtering and prediction problems.