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Introduction, brief description of ring laser gyroscope, the algorithms that are to be analysed, results and conclusion.
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Topic: Analysis of beat frequency estimation methods for the large ring lasers

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SUMMARY

Explanatory note 98 pages, 40 figures, 5 tables, 34 sources, 1 appendix.

KEYWORDS: EARTH ROTATION, FREQUENCY ESTIMATION, SEISMIC SIGNALS, RING LASER, EARTH QUAKE.

The subject of the research is to analyze frequency estimation methods for the large ring laser when monitoring the rotation of the Earth.

This analysis focuses on finding the most effective and efficient technique for estimating frequency of the varying output voltage from the photodetector.

The Earth is normally varies in its rotation rate which is mostly caused by natural phenomenon including Earthquakes, ocean currents, plate tectonics any many other seismic activities. This monitoring of Earth rotation has been done by Very Long Baseline Interferometry (VLBI).

So far the large ring laser gyroscope is currently being used for the purpose thereof, right after the advent of laser, though the technology is still developing especially on Fiber optic gyro. The monitoring is done by estimating the frequency of the output varying voltage from the photodiode during the ring laser operation. Currently, the estimation is done by the Autoregressive technique AR(2), however there are some other techniques that can be used for the purpose, such as Quinn-Fernandes, Pisarenko, weighted average, Hilbert transform (HT), Hilbert Huang transform (HHT) etc. as discussed in chapter three. These techniques are analysed using different data from G-ring laser as well as C-II ring laser for the comparison purpose with the AR (2) technique to obtain the best of all.

The analysis were done based on real data from G-ring laser and C-II ring laser and the results shows the three techniques Quinn & Fernandes, Weighted phase linear predictor and Pisarenko contains oscillations in their outputs which does not reflect the reality when compared to the AR (2). On the other hand Hilbert transform does not fits for the application as it requires large number of sample for precise estimation.

Therefore, the AR (2) has been concluded to be the most efficient and effective technique for the application thereof, though it is only restricted to the low frequency contents of the signal such as micro-seismic events and not to local seismic which contains high frequency contents. For such case the appropriate technique is FM demodulator which is not within the scope of this research.
Аннотация

В работе приводится обзор методов и средств мониторинга вращения Земли с использованием различных методов, таких как интерферометрия со сверхдлинной базой и большие лазерные гироскопы. Более детально рассматривается лазерный гироскоп, поскольку в настоящее время он может быть с успехом использован для этих целей и имеет интересные перспективы.

При использовании большого лазерного гироскопа мониторинг скорости вращения Земли осуществляется путем оценки частоты биений, являющейся выходным сигналом прибора. Оценка в настоящее время выполняется с помощью метода авторегрессии, хотя существуют и другие методы.

В этом исследовании эти методы анализируются и сравниваются с методом авторегрессии для нахождения наиболее эффективного. После анализа наблюдения показывают, что метод авторегрессии хорошо подходит для оценки низкочастотных процессов, в то время как другие оценки, полученные методами Куинна-Фернандеса, взвешенного линейного предсказателя фазы и методом Писаренко, не соответствуют реальному выходному сигналу прибора. Во всех случаях наблюдается колебательный процесс, который отсутствует при использовании авторегрессионного метода.

С другой стороны, преобразование Гильберта не подходит для небольшого числа выборок, но позволяет получить точную оценку частоты. В случае высокочастотного сигнала, который связан с локальными сейсмическими событиями, следует использовать метод частотной демодуляции.
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INTRODUCTION

Normally, the Earth rotation rate is not constant as it varies due to the natural phenomenon specifically seismic activities. For the applications in seismology and geodesy, the rotation of the Earth requires to be monitored by the application of different technology. There are different kinds of technology that are being used to monitor the Earth rotation rate which differ on their resolution.

The current technology is the large ring laser which gains lots of advantages compared to the rest of the techniques due to its capability of being used in both geodesy and seismology. The other technology such as Very-Long-Baseline-Interferometry (VLBI) is only for geodesy and not seismology while others like seismometer array and fiber optic gyroscope (FOG) does not surpass ring laser capability.

The variation of Earth rotation by ring laser is done in an indirect way in which the frequency of the output from the photodiode is to be estimated in a very short period of time for accurate estimation. The estimation is done by autoregressive AR (2) technique currently, however there are some other technique that can also be used for the purpose.

These techniques are Quinn-Fernandes which belongs to an adaptive notch filters and non-Fourier, Pisarenko technique which assumes the signals is a complex exponential with a white noise, weighted average technique which uses kay window in estimation, Hilbert transform and Hilbert Huang transform which works in seminar manner though Hilbert Huang transform is the improvement of Hilbert transform.

However, the research is basically focuses on the analysis of all these techniques using the available real data extracted from G-ring laser and C-II ring laser aiming at finding the effective technique that will perform in a real or near real time. These techniques will be compared to the reference technique which is currently being used for the purpose thereof.
1 Earth rotation

The rotation of the Earth is a natural phenomenon whereby the rotation is from the west towards east. As viewed from North Star or polestar Polaris, the Earth rotates counter-clockwise. The North Pole, also called the Geographic North Pole or Terrestrial North Pole, is the point in the Northern Hemisphere where the Earth's axis of rotation meets its surface. Normally the Earth rotates once per day i.e.24 hours around its own axis with respect to the sun and once for every 23 hours 56 minutes and 4 seconds with respect to the stars.

1.1 Variation of Earth rotation

During its rotation, the rotational speed and the orientation of its axis (North Pole direction) are not constant. The two parameters are continuously changing caused by different phenomenon which are also differ from one to the other. These variations might be caused by lunar gravity and various dynamic phenomenon of the Earth [1] such as earthquake, ocean current, plate tectonics, sea level loading and many others as seen in the figure 1.

![Figure 1 – Forces Disrupting Earth Rotation](image)

Monitoring of the Earth rotation is of vital importance because the obtained information can be used in several applications. These information are necessary to perform orbit control of satellites and space craft including GPS, it also unveil the dynamic of the inner Earth that cannot be directly accessed. Moreover the information is usefully in Geodesy application which help to define and maintain the reference frames i.e. Terrestrial and Celestial planes. The reference frame (terrestrial
reference frames) defines the point position on a global scale with an accuracy of less than 1cm [2] and producing the velocities of each point on the Earth due to plate tectonics.

The computation of a terrestrial reference frame is done by considering the motion and position of the satellites and quasars on the celestial reference frame. The linkage between terrestrial and celestial reference frames is provided by the rotation of the Earth and the instantaneously orientation of the Earth rotation axis. There are different kind of technology that has been implement the purpose of monitoring the Earth rotation which varies continuously due to the above mentioned natural phenomenon. The following subsections explaining the different technology for the purpose thereof.

1.2 Monitoring Earth rotation by geodetic techniques

Before the development of a Ring laser gyroscope (Large ring laser), the Earth rotation parameters were monitored by only the geodetic space techniques one of them which is still in use is the Very Long Baseline Interferometer (VLBI). In the early time before the development of VLBI, the discovery of the radio sources like quasars which emits radio waves continuously located at a far distant from the Earth leads to the establishment of radio interferometry principle in 1967.

At that particular time the interferometric systems had an inter-connection between antennas for receiving signals from the source. This condition leads to the limitation of the distance of separation between antennas and the resolution which were about few hundreds of metre and few milliarcseconds respectively. Hence with the need to measure long baseline (distance between antennas), the removal of the inter-connection between antennas was inevitable which leads to the birth of VLBI technique.

VLBI is an advanced space geodetic technique that can measure a distance of thousands of kilometers between its antennas with an accuracy of few millimeters, by receiving radio signals from the very deep space. The basic observables in geodetic VLBI are time delay which is the difference in the times of arrival of the signal at the two antennas and time delay rate (time derivative of delay). The time delay observable can either be phase delay, based upon phase of the radio signal wave, or group delay.

These VLBI observables contain information related to the length and orientation of the baseline (or relative positions of the antennas), the parameters defining the Earth rotation and polar motion, the atmospheric and other instrumental effects. Thus, it is possible to estimate baselines or Earth rotation parameters from these VLBI observations to a very high degree of accuracy.
1.2.1 Very-Long-Baseline-Interferometer (VLBI) Working principle

During its operation the giant parabola antennas (figure 2) receive faint radio signals emitted from far-distant celestial objects. Due to the position difference between the antennas, there is a slight difference of about 0 to 0.02 seconds [3] between the antennas in the receiving time of a particular signal from the same object. This delay time is measured to a precision of one 10-billionth of a second with a precise atomic clock installed at each antenna.

![Diagram of VLBI process](image)

Figure 2 – Very Long Baseline Interferometer (Geospatial information authority of Japan)

The distances from the objects is obtained by multiplying the delay time and the speed of light on the baseline analysis as shown above. Three dimensions of the objects position relative to each other is obtained by computing the distances of objects at different position in the space. Normally, a single observation lasting for about 24 hours.

1.2.2 Composition of VLBI technique

Generally, the deployment of VLBI technique comprises of different subsystems with distinct function in accomplishing the process. The instrumentation of the technique includes the following subsystems:

- VLBI dish antennas

The dish antenna are of different sizes which varies from 300m in diameter which is permanently installed to the one with 5m in diameter of the mobile VLBI
systems. These antennas collect the weak radio signal for the source and continuously monitor the position of the radio source by rotating in space.

➢ Receiver
This is located at the front of the antennas which receives the signal from distant source and amplifies it to the required amount.

➢ Frequency standard
These are atomic clock which are of rubidium and cesium beam clock type of sometimes hydrogen maser is used to noting the arrival time of the signal. These clock has the stabilities of the order of 1 part in 10¹⁴ or better.

➢ Recording and Correlator unit
The recording units composed of the magnetic disk/tapes which records the received signal and later correlates in the correlating unit for post processing.

➢ Calibration unit
Normally the system is calibrated for the environmental and hardware effects which might leads to errors on the final observation. Hence the calibration is vital to get rid of these effects.

Generally, VLBI is most well-known for imaging distant cosmic radio sources, spacecraft tracking, and for applications in astrometry. However, since the VLBI technique measures the time differences between the arrival of radio waves at separate antennas, it can also be used "in reverse" to perform earth rotation studies, map movements of tectonic plates very precisely (within millimeters), and perform other types of geodesy. Using VLBI in this manner requires large numbers of time difference measurements from distant sources (such as quasars) observed with a global network of antennas over a period of time.

To determine the rotation of the Earth, the principle is the relative measurement of rotation by observing reference objects such as points, stars and satellites outside the rotating Earth. The Earth rotation parameters is provided by considering the time delay of the signals received by the antennas because the delay time is mainly due to rotation of the Earth. Regardless of VLBI possessing the necessary stability and resolution in determining the Earth rotation it is rather based on the involved process and not continuous i.e. it is usually operates once or two times per week.

Other geodetic space techniques for monitoring earth rotation are Satellite Laser Ranging (SLR) which uses the time required by the light from ground based-lasers to bounce off satellites, Global Positioning System (GPS) which relies on travel time of the radio signals between satellites and ground stations and Doppler Orbitography by Radiopositioning Integrated on Satellite (DORIS).
All these techniques require global networks and structures for the observation and data handling, which are coordinated by the international services including IVS, ILRS, IGS and IDS.

1.2.3 Space Very Long Baseline Interferometry technique (Space VLBI)

Due to the vast development in the field of electronics, instrumentation, data processing and analysis, the field of VLBI technique is continuously increasing in its development at a fast pace. With several geodetic VLBI stations continuously carrying out interferometric observations, and new stations being established, and the proposed geodetic VLBI station in varies places, and with the array of mobile VLBI instruments augmenting this global VLBI network, this technique is about to become the most promising high precision geodetic technique in the near future.

The main limitation of the VLBI technique is the physical limitation on length of the baseline due to the size of the Earth, this limitation resulted to the launch of the satellites with VLBI antennas in space. Space VLBI is an extension of VLBI into the space, where one or more of the antennas will be mounted on the satellite. This extended baseline improves the resolution of the system, thus enabling the scientists to study stars and galaxies farther than before. The geodetic applications of this system include orbit determination for the satellites, monitoring Earth rotation, defining Reference Frames, estimating Earth’s gravity field, etc.

1.3 Detection of seismic induced rotation

The VLBI technique is mainly for geodesy and not for seismic detection, this limits the performance of the technique as it does not monitor the Earth variations due to seismic activities which produce rotation waves that varies the Earth rotation. Therefore the detection of seismic induced rotation is also required for monitoring purpose. One of the technique for such purpose is the seismometer array is also referred to as seismic array.

The technique is a system of linked seismometers arranged in a regular geometric pattern (cross, circle, rectangular etc.) to increase sensitivity to earthquake and explosion detection. The seismometers are distributed over an area on the Earth surface with small distance of separation for the purpose of correlating signal waveform between the seismometers. The primary function of seismic array is mainly for detecting the area of the Earthquake focus, epicenter and the hypocenter.
by measuring the arrival time of the seismic waves as they are received by the seismometer.

However on the other hand the rotation motion can also be detected by seismic array with analogy to translation motion detection. This was realized in the experiment performed by the group of Prof. Igel in 2004 [4]. In the experiment the rotation rate was derived by taking derivatives of the velocities recorded by the seismometers using the method of triangular grid. The rotation rate of the Earth is then calculated by using the following equations after taking the first order spatial derivatives of the linear interpolated function.

\[
\frac{\partial_x V_y}{\partial y} = \frac{1}{A} \left[ b_i V_y^j + c_j V_y^j + b_k V_y^k \right] \\
\frac{\partial_y V_x}{\partial x} = \frac{1}{A} \left[ c_i V_x^i + c_j V_x^j + c_k V_x^k \right]
\]  

(1)  
(2)

The principle of the measurement is presented in figure 3.

Figure 3 – Seismic array for rotational measurement

Despite of the technique being capable of detecting rotational rate of the Earth, there are still difficulties especially on deriving the rotational rate from array due to noise level in the seismometer which varies due to different ground coupling in which the small difference in noise level results to poor calculations. Moreover, regardless of its simplicity and low cost it is still vulnerable to many complications
like variations in the location sites nature which may affect the response of the instruments.

1.4 Monitoring Earth rotation by optical gyroscope

Monitoring of the Earth rotation and orientation of its axis is also done by the absolute measurement of rotation by using optical gyro which is a completely different approach compared to the previous techniques. The distinction of these techniques to the rest of the method is that they work based on the Sagnac principle in which the phase or frequency difference of the coherent light is used to determine the Earth rotation. The optical gyro method include two instruments which are Fiber optic gyroscope and Ring laser gyroscope.

1.4.1 Monitoring Earth rotation by Fiber optic gyroscope (FOG)

Fiber optic gyro is the prominent instruments that is widely used in the inertia navigation with the advantages of being simple during its production, performance improving and relatively low cost in its production and maintenance. During its operation, two beams from a laser are injected into the same fiber but in opposite directions. Due to the Sagnac effect, the beam travelling against the rotation experiences a slightly shorter path delay than the other beam. The resulting differential phase shift is measured through interferometry. The strength of the Sagnac effect is dependent on the effective area of the closed optical path which is normally enhanced by the number of turns in the coil.

The phase shift/phase difference of the two beams becomes the output of the fiber optic gyroscope which is proportional to the rotation of the Earth. The general equation relating the FOG geometry and the phase difference of the beams ($\Delta \varphi$) is given in the equation below:

$$\Delta \varphi = \frac{2 \pi L D}{\lambda c} \Omega ,$$

where $L$ - the total length of the optic fiber, $D$ – mean diameter of the coil and $\Omega$ - Earth rotation, $\lambda$ - wavelenghth of light, $c$ - speed of light.

The Earth diurnal rotation was detected in the experiment performed by the Doug Marret and his team. The design used was a fiber optic gyroscope (FOG) using a single mode which is of a low cost than the polarization maintaining fiber. The
wavelength of the laser chosen was 1310 nm and a 1 mV DFB laser source. The complete schematic of the fiber optic gyroscope (FOG) is shown in figure 4;

![Figure 4 – Fiber Optic Gyroscope](image)

The detection of the phase difference between the two counterpropagating beams is done by a photodiode as shown in the above figure while the second reference PIN photodiode built in to the DFB laser is used as a comparison voltage source for a common mode rejection amplifier which amplifies the voltage difference detected by 500x to as much as 1150x.

To achieve the required resolution of the apparatus, three features were included as explained below:

- the fiber optic loop is made long about 1 km in length which gives 318.5 wind of cable on the loop resulted to an area of 250 m² in total;
- to maximize the angular velocity of the loop due to Earth rotation, requires the radius to be as large as possible which was made to be 0.5 m giving the total circumference of 3.14 m. This gives the maximum angular velocity of the apparatus of 3.6x10⁻⁵ m/s due to Earth rotation.
- and also high amplification of the base D.C. signal to make the small velocity differences detectable.

Generally, the experiment were conducted twice in which in the second experiment the amplification was increase aiming at reducing the noise in the apparatus. In the first experiment the angular velocity of the loop (3.6x10⁻⁵) gives rise to the amount of fringe shift of 4.5x10⁻⁵ between two beams while in the second experiment due to high amplification used in the system, the fringe shift between two beams was in the order of 7.0x10⁻⁵ per mV.

Nevertheless, the research group in Polis Institute of applied physics also designed and manufactured the FOG aiming at detecting the seismic induced rotation on the Earth [5]. The total length of the FOG was 400m with the diameter D=0.2 m. The sensitivity of the rotation rate achieved after the running of the
instrument was about $9.8 \times 10^{-6}$ rad/sec which is at least viable for teleseismic or earthquake with small magnitude. However the advantages of the FOG can be implemented in the seismically active areas and not far apart from the instrument.

### 1.4.2 Monitoring Earth rotation by Ring laser gyroscope (RLG)

The ring laser gyroscope was initially used for inertial navigation purpose in a moving object for sensing and measuring a very small angles of rotation. At that particular time till to date the ring laser has gained a leading position in that field due to its large dynamic range, high precision, small size and the advantage of not requiring any moving mechanical parts [6].

However, the small size of the gyroscope, their resolution and stability were not enough to detect the variation of the Earth rotation. This prompted the idea of the extension of the perimeter of the ring laser gyroscope as it was proved that the sensitivity of the ring laser increases with their perimeters. Finally after the extension of the perimeter with highly symmetrical design, high quality faction (Q-factor) and high mechanical stability makes the instruments with the required sensitivity [7] of the Earth rotation variation after being installed in underground.

![Figure 5 – Schematic section of underground ring laser](image)

The main distinguishes between fiber and ring laser gyro is in the measurement of the rotation rate in which in fiber the rotation rate is computed form the phase shift between the two beams while in ring laser gyroscope the rotation rate is computed form the frequency difference of the two counterpropagating beams. Moreover, the performance of the ring laser surpass that of the FOG as in FOG, there is the problems of thermal susceptibility and nonreciprocity which affect to the large extent its performance. On the other hand Very-Long-Baseline-Interferometry
(VLBI) provide an accurate measurement of the length of day (Earth rotation) with uncertainty of less than 0.1ms per day.

The measurement are performed by a set of globally distributed radio telescopes and with respect to a reference frame of quasar positions. In comparison with ring laser, the measurement is carried locally and normally within a short interval of time in a continuous manner which very advantages as compared to VLBI. In addition as explained earlier that the Earth rotation is not constant, that means there are natural phenomenon which causes the variation of the rotation that includes seismic activities like earthquakes, ocean loading, tectonic plates movements etc.

For that case when these activities takes place and leads to variations in Earth rotation, the output of the ring laser measurement contains those effects in the Earth rotation. This is not possible to be detected by the Very-Long-Baseline-Interferometry and hence makes it less superior than the ring laser gyroscope. Therefore based on the advantages of ring laser gyroscope, it is now becomes the main instrument for monitoring the Earth rotation variations and orientation of its rotation axis in a continuously manner including those resulted from seismic events. The more details of the large ring laser gyroscope are discussed in the next chapter.

### 1.5 Problem statement

Monitoring of the Earth rotation rate by using ring laser gyroscope (RLG) is done in an indirect way as compared to seismometer where the output signal is simply scaled ground velocity [8]. The output from Large ring laser is a raw data (signal) with a carrier frequency of the rotation rate consisting of some other frequency components specifically those of seismic activities i.e. Earthquakes. This frequency needs to be determined at a very short time interval in order to obtain the precise value of the rotation rate with a very small error.

Figure 6 shows the waveform of the output signal from the ring laser which is the varying voltage with time due to the Earth rotation. Therefore, the requirement here is to estimate the frequency of the output which is marked by dotted lines and the dark arrow from peak to peak. Normally the waveform is not as clear as that picture instead it varies with a very high rate which is impossible to determine in a normal conventional ways like manual calculation of frequency by determining the period of the waveform. In that manner, the frequency is therefore required to be estimated in a very short period of time to ensure minimum error in the final estimation of the frequency. This requirement brought the need to have a frequency
estimation technique that has the capability of estimating the frequency of varying output signal from the ring laser.

![Figure 6 – Example of photodiode output on the G-ring laser](image)

So far, the estimation of frequency of the output signal is being done by the use of Autoregressive Technique (AR (2)). However despite the fact that the technique is robust, there are also some other counterpart techniques that might also be used for estimation with the probability of being superior to the AR (2) specifically on the acquisition rate (near real time), noise level and the level of complexity.

Therefore, the research is basically focuses on detail examination of different frequency estimation techniques aiming at obtaining the efficient and effective one by taking Autoregressive (AR (2)) technique as a reference. The estimation is based mostly on the outputs obtained from G-ring laser and some few data form C-II ring laser though is no longer used effectively as compared to G-ring laser.
2 Ring laser gyroscope

The ring laser gyroscope is an extremely useful instrument for sensing and measuring very small angles of rotation of the moving objects. It has now replaced the mechanical gyroscopes used in most of the aircraft (both civil and military) and also in long range guided missiles. The idea of laser gyroscope came shortly after the discovery of laser when Rosenthal presented a paper in 1992 [9] suggesting the ring laser. With the ring laser, one could distinguish two beams in opposite directions. This phenomenon was first observed by Sagnac who did a series of experiments following the theory of aether whether it is exist or not and finally he observe that phenomenon which leads to contradiction and giving up with the theories of his predecessors.

2.1 Sagnac effect

This effect was discovered by a French scientist George Sagnac, who was the first to correctly combine the theoretical expectations with an experiment. He set a coherent beam of light, which he guided around a contour with a predetermined area of 0.086 m$^2$. The entire apparatus was then rotated with a frequency of approximately 2 Hz. With the help of a beam splitter and several mirrors he observed two counter-propagating beams passing around the same optical path.

He observed a shift in the interferogram of 0.07 ± 0.01 fringes and found that the measured shift was directly proportional to the rate of rotation. He build the instrument with sufficient mechanical stability such that no bending of optical components under the substantial centrifugal forces had an impact on his measurements and the observation was referred to as the “Sagnac effect” [10].

Dealing with non-inertial rotating frame, the rigorous treatment of the Sagnac effect involves the general theory of relativity. However, a classical result can be obtained, correct at the first order in the velocity $v/c$, where $c$ is the speed of light [11, 12]. During his experiment, he obtained the phase difference ($\delta \phi$) given by the equation below;

$$\delta \phi = \frac{8\pi A}{\lambda c} n\Omega,$$

(4)

where $A$ is the area circumscribed by the laser beams, $\lambda$ the optical wavelength, $c$ the velocity of light, $n$ the normal vector upon $A$, and $\Omega$ the rate of rotation of the interferometer. Equation above relates the obtained phase difference to the rate of rotation of the entire apparatus and can be interpreted as the gyroscope equation [13].
Generally, rotation sensing gyroscopes which utilize the Sagnac effect in the optical domain, essentially fall into two categories:

➢ passive;
➢ active.

2.1.1 Passive interferometer

A passive ring interferometer uses light entering the setup from outside in two opposite direction. The interference obtained is a fringe pattern, and what is measured is a phase shift. This was demonstrated by Sagnac in the experiment in 1913. In the experiment for conceptual simplicity he considered the rotating ring interferometry by using classical theory of relativity.

Figure 7 – Sagnac interferometry

Figure 7 above shows an ideal circular interferometry of with radius R. Light enters at point A and split by the beamsplitter, then constrained to travel along the circumference of the circle and finally recombines at the original beamsplitter. When the interferometry is stationary, there will be no any difference of path length travelled by two opposite beams, hence no phase shift detected.

In the other hand, when the interferometry is rotating with a constant angular velocity (Ω) as shown above, the path length of the two beams become different where the one travelled in the same direction as the interferometry will have to travel a longer distance while the other in the opposite direction will have to travel a shorter distance.

In this manner the beams will not recombine at the same point where they had split (point A) instead they will recombine at point B. Therefore the difference in closed path difference (ΔL) between the two counterpropagating beams for a
rotating interferometry was given by the equation below which relates both its rotation speed and the enclosed area.

\[ \Delta L = \frac{4A\Omega}{c}, \]

where \( A \) - area of the path, \( c \) - speed of light and \( \Omega \) - rotation of the interferometer.

However the sensitivity of the interferometry becomes the main problem due to the path difference between the two beams being very small compared to the wavelength of the light. This prompted the need for an alternative design which will increase the sensitivity and finally the new set up which uses light source inside the interferometry instead of external light source. This was referred to as active interferometry as explained in the following subsection.

### 2.1.2 Active interferometer

The difficulty in using passive interferometer arises from the lack of sensitivity since the difference for the light travelling in the two directions is much less than a wavelength. The use of a laser as the external source of light does not improve the sensitivity of an instrument. However, if the system is made into active interferometer, the sensitivity is improved.

With the advent of lasers it was possible to increase the resolution of Sagnac interferometers substantially. In particular, the transition from phase to frequency measurement provided for a vast improvement in sensor sensitivity. By placing a laser gain medium inside the closed light path established by four or three mirrors converts the apparatus into a traveling wave laser with a square or triangular cavity [14]. Specifically, the report will be focusing on large helium-neon based ring lasers for monitoring Earth rotation and associated effects. However, there are a wide variety of alternative active laser interferometers as outlined in table 1.

In an active interferometer, the medium emit light beams which travels along the same path in different directions and finally the beat frequency is obtained after they undergo interference. A good example of active interferometer is a ring laser as shown in figure 8 which is simply consist of four corner mirror for reflecting the light inside the cavity in which laser medium is placed and the other arms for keeping the laser beam till it comes out from one of the mirror with photodetector connected to it.
Table 1 – Different types of laser medium

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Wavelengths</th>
<th>Areas of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium–Neon (He-Ne) laser</td>
<td>632.8 nm</td>
<td>Interferometry, holography, spectroscopy, barcode scanning, alignment, optical demonstrations</td>
</tr>
<tr>
<td>Argon laser</td>
<td>(454.6,488,514.5)nm</td>
<td>Retinal phototherapy (for diabetes), lithography, confocal microscopy, spectroscopy pumping other lasers</td>
</tr>
<tr>
<td>Krypton laser</td>
<td>(416,530.9,568.2)nm</td>
<td>Scientific research, mixed with argon to create &quot;white-light&quot; lasers, light shows</td>
</tr>
<tr>
<td>Nitrogen laser</td>
<td>337.1nm</td>
<td>Pumping of dye lasers, measuring air pollution, scientific research</td>
</tr>
<tr>
<td>Carbon dioxide laser</td>
<td>10.6μm, (9.4μm)</td>
<td>Material processing (engraving, welding, etc.), photo acoustic spectroscopy</td>
</tr>
</tbody>
</table>

The introduction of laser medium inside the ring laser, makes it to be more sensitive compared to passive in which the laser source is located outside the apparatus.
Both ring laser and fiber optic gyroscopes have exhibited the ability to perform under adverse environmental conditions where mechanical devices would be hard pressed to operate. Both have proven to be viable contenders to mechanical systems and continue to make inroads into what were once exclusive domains of mechanical devices.

### 2.2 Principle of operation

Generally, the ring laser is attached to an object for which its rotation speed needs to be determined by the instrument. As the object rotates, the two counterpropagating beams start to differ in their frequencies and the beat frequency is obtained from the output signal of the laser gyroscope. The beat frequency obtained due to rotation is proportional to the product of the geometric area ($A$) enclosed by the laser beams and the rotation rate ($\Omega$) imposed on the cavity and inversely proportional to the wavelength ($\lambda$) of the laser and the perimeter ($L$) and the normal vector $n$.

Mathematically, it is expressed as shown below;

$$\Delta f = \frac{4A}{\lambda L} n\Omega$$  \hspace{1cm} (6)

Ring laser gyroscope uses three mirrors forming a triangular path for the beam of laser light as shown in figure 9.

![Figure 9 – Schematic diagram of a ring laser](image)
2.3 Construction of ring laser gyroscope

The ring laser gyroscope basically consist of a ring cavity around which two laser light beams travel in opposite directions. Mirrors are used to focus and redirect the laser beams at the corners. Critical variables in the construction of a ring laser include the following:

➢ size: larger ring lasers can measure lower frequencies. The sensitivity of large rings increases with size;
➢ mirrors: it is essential for a high quality ring to use mirrors of very high reflectivity. Metallic mirror surfaces are inadequate for laser work (household Al-covered mirror surfaces are 83% reflective, Ag is 95% reflective). Hence highly reflective mirror is required to avoid losses due to absorption and transmission;
➢ stability: the assembly must be attached to or built within a substance that changes minimally in response to temperature fluctuations (e.g. Zerodur, or bedrock for extremely large rings);
➢ gas: He-Ne generates beams with the most desirable features for large ring lasers. For gyros, in principle any material that can be used to generate monochromatic light beams is applicable.

The number of mirrors might be three of four, but more suitable one is the one with three mirrors as it is simple compared to the one with four mirrors as it is difficult during construction and might leads to number of errors during operation.

Ring laser gyroscope has gained a great importance in the marked and technology in general over the mechanical gyros due to the following reasons:

➢ non-existence of moving parts;
➢ high capability;
➢ higher reliability as compared to the mechanical gyroscope;
➢ in addition, the laser gyroscope is capable of wide dynamic range and rapid reaction time, which is the characteristics required for missile guidance.

2.4 Large Ring Laser

Despite the fact that laser ring sensors are widely used for detecting the rotation of the moving objects but their resolution and stability are not good enough for the accurate measurement of fluctuations of Earth rotation for applications in geodesy and geophysics.

Large ring lasers have the potential to be used for measuring the fluctuation of Earth rotation with the following features distinguished from the conventional ring lasers:
➢ the extension of the perimeter along with a highly symmetrical design of the cavity;
➢ large laser ring are designed with a high mechanical stability;
➢ reduction of “lock-in” effect which was the major source of error on determination of the difference in frequency between two counter propagating beams;
➢ large ring laser also provide very high sensitivity resulted from a high quality factor (Q).

After theoretical investigations have shown that large ring lasers have basically the potential to detect Earth rotation variations [15], the Forschungsgruppe Satellitengeodäsie (FGS) decided in 1990 to develop a large ring laser for Earth rotation monitoring. The development of large ring laser was based on the improvement of the instruments time to time as explained in the following subsections.

2.4.1 The C-I ring laser

At this time the feasibility of large laser gyroscopes was demonstrated at the University of Canterbury in Christchurch, New Zealand [16]. This "Canterbury Ring" which is referred to as a “C-I” spanned an area of roughly 0.75 m² and obtained a beat frequency of nearly 71 Hz.

Though it was the first large ring laser that unlocked due to the Earth rotation, its mechanical design did not allow routine measurements over a long period of time. The diagram below shows Canterbury Ring (C-I).

![Figure 10 – Ring laser C-I](image)

Since C-I ring laser do not sustain for a long term stability, the Forschungseinrichtung Satellitengeodäsie (FESG) of the TU Munich and the
Bundesamt für Kartographie und Geodäsie (BKG) developed a ring laser of similar size especially for long term stability.

2.4.2 C-II ring laser

This prototype of the ring laser (C-II (figure 8)) was constructed and build by the company Carl Zeiss in Oberkochen (Germany) in which the key technologies were the application of the glass ceramic Zerodur as the base material for geometric stability and the optical contacting to obtain a perfect vacuum seal.

The prototype shows the expected Sagnac frequency of 79.4Hz and its ability for long-term operation. However, the size of 1 m\(^2\) is too small to resolve changes in Earth rotation.

After the basic technologies for the construction of a large ring laser for Earth rotation monitoring has been tested successfully, still there was a doubt about the operation of a large ring laser using a mono-beam mode.

![Figure 11 – Ring laser C-II](image)

2.4.3 The G-0 ring laser

To ensure the feasibility of a large ring laser operation under single mode regime, a large ring laser but simple was designed and constructed with an area of 12.25 meter square [17] ring laser located at the Cashmere Cavern Laboratory and mounted vertically on one of the existing concrete walls This second prototype called G-0 (figure 9) had first light in 1998 showing the expected Sagnac frequency
of 288 Hz. The G-0 ring laser was installed vertically on the wall as shown in figure 12.

![Figure 12 – G-0 ring laser](image)

The main reason for constructing G-0 was to further the work done by C-2 in preparation for construction of the Gross Ring. While constructed using much cheaper materials than C-2, G-0 provide insight into issues of extrapolating to a much larger size.

G-0 has successfully measured fluctuations in earth rotation to an accuracy 10 parts per million [18] of the base rate. When working in conjunction with C-2, the rotational effects of teleseismic waves have been detected. Its vertical orientation is an added bonus for geophysical studies as it measures Rayleigh (vertically polarized) waves, whereas C-2 measures Love (horizontally polarized) waves.

### 2.4.4 The Gross (G)-ring laser

The large ring laser G is like C-II made of Zerodur, but in a semi-monolithic construction due to the fact that it was not possible to obtain Zerodur in a sufficiently large slab. Hence the G-ring was constructed on a rigid circular baseplate with a diameter of 4250 mm and a thickness of 250 mm with an effective area of 16m² circumscribed by the laser beams as shown in figure 13.
Note: The C-II and G-ring installation have been made such that both the sensor normal vector and local “g” are aligned to be parallel. Relative changes between local “g” and the ring laser normal are monitored by high resolution tiltmeters. Figure 14 below shows the relationship for a sensor located at given direction (Θ).

G-Ring Laser is the most stable ring laser and has the highest usable sensitivity, though there are a number of large ring lasers used before G-Ring laser as explained in the development era. Table 2 summarizes the different types of large ring lasers, with size (area A), quality factors (Q), Sagnac frequency (fsag), lock-in threshold (flock), finesse and Ringdown time.
Table 2 – Summary of different kinds of large ring laser

<table>
<thead>
<tr>
<th>Ring Laser</th>
<th>Area (m²)</th>
<th>Q. factor</th>
<th>Sagnac freq.(HZ)</th>
<th>Lock-in freq.(HZ)</th>
<th>Finesse</th>
<th>Ringdown time.(μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-II</td>
<td>1</td>
<td>5.3 x 10¹¹</td>
<td>79.4</td>
<td>0.24</td>
<td>85000</td>
<td>180</td>
</tr>
<tr>
<td>GEOsensor</td>
<td>2.56</td>
<td>3.0 x 10¹²</td>
<td>102.6</td>
<td>0.014</td>
<td>300000</td>
<td>1000</td>
</tr>
<tr>
<td>G-0</td>
<td>12.25</td>
<td>2.5 x 10¹²</td>
<td>288.6</td>
<td>0.013</td>
<td>113000</td>
<td>829</td>
</tr>
<tr>
<td>G-ring</td>
<td>16</td>
<td>3.5 x 10¹²</td>
<td>348.8</td>
<td>0.01</td>
<td>138000</td>
<td>1200</td>
</tr>
<tr>
<td>UG1</td>
<td>77</td>
<td>1.2 x 10¹²</td>
<td>1512.8</td>
<td>0.01</td>
<td>2100</td>
<td>409</td>
</tr>
<tr>
<td>UG2</td>
<td>121.4</td>
<td>1.5 x 10¹²</td>
<td>2180</td>
<td>0.008</td>
<td>1100</td>
<td>640</td>
</tr>
</tbody>
</table>

2.5 Application of Gross (G) ring laser in measuring the Earth rotation rate

In measuring the rotation of the Earth using large ring laser, the Sagnac frequency obtained is used as a measure of the Earth rotation as mentioned before. For applications in geodesy and geophysics specifically, the fundamental observable, the Sagnac frequency is strongly influenced by three factors:

a) Scale factor

The variability of the sensor geometry and effects from laser functions (such as dispersion, laser gas aging, and backscatter coupling) reflect themselves in the measurement quantity mostly as a slowly changing bias.

b) Sensor orientation

The alignment of the normal vector of the sensor with the Earth rotation vector as a function of time is critical. Pressure loading around the sensor site, varying wind loads, ground water variations, micro-seismic activity, and solid Earth tides can be readily visible.

c) Environmental factors

Environmental factors like fluctuation of temperature, pressure and humidity, reduce the Q-factor of a resonator, change its effective optical length and create different Q-factors for each counter-propagating beam, hence these also must be monitored to insure the correct measurement is obtained.

d) Variations of Earth rotation due to natural phenomenon

Since the Earth's rotation is not even. Any motion in/on the Earth causes a slowdown or speedup of the rotation, or a change of rotation axis. The natural
activities in the Earth such Earthquakes, ocean loading, tides etc. has a noticeable effects on the Earth rotation speed which might be lowered or increased depending on the activity nature. These variations are detected by the ring laser and observed on the output Sagnac frequency.

Generally, the scope of this research is mainly focuses on the variations of the Earth rotation rate resulted from seismic activities. The Earth rotation rate in the absence of any seismic activities detected by the G-ring laser is normally uniform with some noise contents. This is observed from the output signal of the G-ring laser on the photodetector. In the presence of seismic activities such as earthquake, the uniformity of the Earth rotation rate in the output on the photodetector changes and vary either with a low rate of faster rate depending on the activities. The variations of Earth rate might be related to teleseismic activities in which the place of events is located at a distant from the G-ring laser or local events whereby the source of events is very close to the G-ring laser.

2.5.1 Seismic induced rotation

Earthquakes are usually caused when rock underground suddenly breaks along a fault. This sudden release of energy causes the seismic waves that make the ground shake. When two blocks of rock or two plates are rubbing against each other, they stick a little. The rocks are still pushing against each other, but not moving. After a while, the rocks break because of all the pressure that's built up.

When the rocks break, the earthquake occurs. During the earthquake and afterward, the plates or blocks of rock start moving, and they continue to move until they get stuck again. The spot underground where the rock breaks is called the focus of the earthquake. The place right above the focus (on top of the ground) is called the epicenter of the earthquake.

Earthquake-like seismic waves can also be caused by explosions underground. These explosions may be set off to break rock while making tunnels for roads, railroads, subways, or mines. These explosions, however, don't cause very strong seismic waves. You may not even feel them. Sometimes seismic waves occur when the roof or walls of a mine collapse. These can sometimes be felt by people near the mine. The largest underground explosions, from tests of nuclear warheads (bombs), can create seismic waves very much like large earthquakes.

These seismic waves produce the ground motion both linear and rotational. Normally, there are many types of seismic waves but mostly four types are considered which includes:
➢ compressional or Primary (P) waves;
➢ transverse or Secondary (S) waves;
➢ love wave;
➢ Rayleigh wave.

The primary and secondary waves are referred to body wave due to their propagation on the body of the Earth while the latter two are called surface waves as they propagate along the surface of the Earth. Figure 15 shows the form and propagation direction of the waves.

Both wave have different amplitudes and travel times and produce rotational motion of the ground except for P-wave which moves the matter in a contraction expansion way (fig.16 (a)). However, the P-wave can cause rotation when it reflects from the Earth surface and generates S-wave (known as P-S conversion). The shear and Rayleigh waves cause rotation in the vertical plane while Love waves generate rotation in the horizontal plane.

Generally, the seismically induced rotation rate on Earth can be represented by the following equation;

\[
\Omega_s = \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \frac{1}{2} \nabla \times V = \frac{1}{2} \begin{pmatrix} \partial_y V_z - \partial_z V_y \\ \partial_z V_x - \partial_x V_z \\ \partial_x V_y - \partial_y V_x \end{pmatrix} 
\]

(7)

where \( V_i, i = x, y, z \) are the components of the velocity field \( V \), the time derivative of the deformation field \( U \) [19]. The corresponding Sagnac frequency also includes such terms as strain and tilt that arise from the changes in perimeter, area and orientation of the ring during the seismic event. However the strain is much
smaller than the actual seismic rotation and is difficult to detect while the tilt input is usually no more than a few percent of the magnitude of the rotational signal and can be detected independently and corrected for.

Moreover for the teleseismic waves, particularly Love and shear waves, there should be a similarity in phase for the vertical component of the rotation rate and translational acceleration [20]. Normally, the magnitude of the Love wave seismic velocity can be varying within the range of 3000 up to 6000 m/s. For the teleseismic event there are no substantial changes of the value of the incoming Love wave expected as well as no variations in the direction.

2.5.2 Requirement for detecting seismic rotation waves

Before the advent of laser followed by the construction of large ring laser, the magnitude of seismic induced rotation on the Earth rate were considered to be very small [21] not just because of any proof, but because there were no any instruments with such resolution of detecting those waves. At that particular time the available instruments were not able to detect the waves due to their resolution being low compared to what was required to be detected.

The superior resolution of large ring lasers along with their insusceptibility to acceleration makes the application of these instruments very attractive for seismological studies. The expected angular velocities to be detected are in the range of $10^{-14} \text{rad/sec} \leq \Omega_s \leq 1 \text{rad/sec}$ and frequency of the signal for seismic waves lies in the range of $0.03 \text{Hz} \leq f_s \leq 10 \text{Hz}$. During the ring laser operation, the Sagnac frequency is obtained in an indirect way in which the raw data from the instrument is divided into beams of specified time window and the Sagnac frequency is estimated using a specified frequency estimation technique.

The standard acquisition rate of seismic signal which covers most of the frequency contents associated with seismic activities is 20Hz which is equivalent to the time of 0.05sec. This means that in every 0.05sec, the Sagnac frequency is estimated. However, the acquisition rate may vary depending on the frequency of the waves to be detected. For the teleseismic wave normally the frequency content are not very high so the time window is not restricted to be 0.05sec, it can be higher than that i.e. 1sec.

For local seismic activities the frequency contents is higher that they may reach up to 10Hz and for this, the acquisition rate must be high i.e.0.05sec (20Hz) which is the standard acquisition rate. The estimation of raw data from the G-ring laser or C-II is can be done by different frequency estimation techniques which differ
in their performance such as accuracy, amount of time, level of complexity etc. As explained earlier, the research aimed at comparing these frequency estimation techniques inorder to obtain the efficient one, their description is in the following chapter.
3 Frequency estimation algorithms

When operating a large ring laser aiming at determining the variation of Earth rotation, the interference of two counterpropagating beams on a ring laser, results to a beat frequency which is proportional to the Earth rotation. The signal with a carrier frequency is digitized at a given sampling rate depending on the specification to estimate the beat frequency.

The digitized signal varies in a very fast rate which is difficult to estimate its frequency in a normal conventional ways. The estimation of a beat frequency can be done indirectly by the application of different techniques.

In frequency estimation, not all techniques gives out the precise results as compared to the theoretical value obtained. There are techniques which gives the best estimation as compared to others due to their efficiency being different depending on the following factors:

a) Elapsed time

This is the time for which a given technique is used to execute the digitized signal for estimating the frequency of the varying signal. The less the time spent by a given technique, the more efficiency it is.

b) Estimation accuracy

The estimations is done in a sample wise as specified in data acquisition rate. This will results to a number of estimated frequencies which varies from one another due to different factors which are inevitable. However, the variations of estimated frequencies must not be large with the exception of aperiodic events which may cause large variations.

c) Computational complexity

The algorithm of a given technique should at least be flexible and easy to apply for any set of data obtained from the instrument at any time.

d) Threshold analysis

When the signal-to-noise ratio (SNR) is low most estimators exhibit thresholding phenomenon which is the representation of a marked decrease in performance relatively to small change of a SNR.

Generally, there are bunch of frequency estimation techniques, but their application depending on the kind of data from which the frequency is estimated. Among many areas which uses estimated frequency for further analysis are in medicine especially on monitoring the hearth rate [22], determination of Earth rotational rate, carrier recovery in communication systems [23], determination of
object position in radar and sonar systems [24], vibration analysis in machines and buildings etc.

Specifically, in this research the four techniques for estimating earth rotation speed with the variations imposed by seismic activities (teleseismic or local seismic) will be examined and compared to draw the conclusion of which one is sweet for the application thereof. The brief overview of those techniques are described below without going into their deep mathematical context.

3.1 Autoregressive second order (AR (2))

The autoregressive second order was implemented by B. Tom King for the purpose of estimating the beat frequency of a Ring Laser Gyroscope (RLG) and its spectral line width. The method assumes the signal to be monochromatic with the deviations caused by white noise.

Generally, the second order autoregressive (AR (2)) technique is based on two parameters such as \( a_1 \) and \( a_2 \) [25] as given in the model below:

\[
\epsilon(t) = y_t + a_1 y_{(t-1)} + a_2 y_{(t-2)}
\]  

(8)

where \( \epsilon(t) \) – noise imposed, \( y_t \) – discrete time sample of the data set

The parameters of the model is chosen so that the time series to behave in a pseudo-periodic form. The model parameters also need to be estimated and it is done by the use of Yule-Walker estimator as given below:

\[
\beta = \begin{bmatrix} C_0 & C_1 \\ C_1 & C_0 \end{bmatrix}^{-1} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix}
\]

(9)

where \( C_j = T^{-1} \sum_{t=j}^{T-1} y_t * y_{(t-j)} \)

(10)

and \( T \) is the sample period.

Finally the frequency \( f \) is calculated from the formula below:

\[
f = \cos^{-1}\left( -\frac{\beta_1}{2\sqrt{\beta_2}} \right)
\]

(11)

To estimate the frequency and spectral line width of a Sagnac signal, B Tom King (7 July 1998) developed the algorithm that can be executed in matlab or
LabVIEW and the obtained values can further be plotted graphically to observe frequency variations and the efficiency of the technique.

He developed a matlab function with the following two output parameters which are the estimated frequency and the line width while the input parameters are the output signal, sampling rate number of sample in each estimate and filter size.

The obtained frequencies can then be plotted with respect to time to observe the variations in Earth rotational speed.

Autoregressive technique is considered a robust usually applied with a bandpass filter and it is mostly applicable in seismic analysis accompanied with the following advantages:

➢ AR (2) is a very robust technique with respect to the changes in frequency;
➢ the frequency estimate can be done online at a high rate;
➢ it is well suited for dynamic situations such as seismic events on monitoring the variations of Earth rotation [26];
➢ stable for short segment of signal.

Regardless of the advantages mentioned above, still the method has got some disadvantages as explained below:

➢ the precise estimation is only for the filtered input, thus the technique is usually susceptible to noise;
➢ it takes a bit longer to compute the frequencies;
➢ it is an irreversible technique.

### 3.2 Quinn-Fernandes frequency estimator

This is a non-Fourier technique which is iterative and can be applied entirely in the time domain. It uses notch filtering and relies on the iterative construction of a filter that cancels an instability at the desired frequency. Generally, the method belongs to an adaptive notch filters class with the general idea of introducing a filter that removes a particular frequency from the signal, the “notch” frequency [27].

If for example the signal is composed of a white noise, finding the notch frequency that minimizes the variance of the filtered signal, it is equivalent to finding the frequency of the sinusoid. The technique requires first the initial estimate of the frequency i.e. qubit frequency and its accuracy will have an effect on the accuracy of the final estimates because it affects the convergence properties of the minimization procedures used by the technique.
The technique has the properties of being fairly insensitive to inaccuracies in the initial estimates for sinusoidal signal with low to moderate noise levels, but for the very low signal-to-noise ratio and the qubit oscillation is affected by back-action of the measurement, the accuracy of the initial estimates is very important. Generally, the accuracy of the technique depends on the following:

- the technique performs much better when the noise level is lowered, that is when the signal-to-noise ratio is increasing by a factor of about 3 to 4 which will increase the accuracy of the technique significantly;
- to have the best final estimates of the frequency, the initial estimate is required to be perfect.

Quinn and Fernandes have suggested in estimating two parameters which are \( \alpha \) and \( \beta \) in the following equation:

\[
y_t - \beta y_{t-1} - y_{t-2} = \varepsilon_t - \alpha \varepsilon_{t-1} + \varepsilon_{t-2}
\]

Subject to \( \alpha = \beta \). The algorithm is then proceeds as follows:

a) set \( \alpha = \alpha_1 = 2 \cos(\hat{\omega}_i) \) where \( \hat{\omega}_i \) is some initial estimate of the \( \omega \) and set \( j = 1 \);

b) filter the data to generate new values \( \zeta_{t,j} \)

\[
\zeta_{t,j} = y_t + \alpha_j \zeta_{t-1,j} - \zeta_{t-2,j}; \quad t = 0, \ldots, T - 1;
\]

where \( \zeta_{t,j} = 0 \) for \( t < 0 \);

c) form \( \beta_j \) by regressing \((\zeta_{t,j}, \zeta_{t-2,j})\) on \( \zeta_{t-1,j} \)

\[
\beta_j = \frac{\sum_{t=0}^{T-1}(\zeta_{t,j} + (\zeta_{t-2,j}) \zeta_{t-1,j})}{\sum_{t=0}^{T-1} \zeta_{t-1,j}^2}; \quad (14)
\]

d) if \( |\alpha_j - \beta_j| \) is small enough, set \( \hat{\omega}_o = \cos^{-1}(\frac{\beta_j}{2}) \) and terminate, otherwise put \( \alpha_{j+1} = \beta_j \), and repeat the procedure from step two.

The estimation can also be done by coding and use Matlab to find the frequencies based on the number of samples for each estimate. Quinn and Fernandes develop a function with only one output which is the Quinn-Fernandes estimates for \( N \) samples and the input is the time series signal obtained from the Ring laser.
3.3 Pisarenko harmonic decomposition

This is also the method of estimating frequencies that rely on the following assumptions during its performance.

➢ The signal $x(n)$ consist of $p$ complex exponentials in the presence of white noise whereby the number of complex exponentials must be known a priori which might be the limit for its usefulness.

➢ It also assumes that $p + 1$ values of the $M \times M$ autocorrelation matrix are either known or estimated (Pisarenko [1973]). Thus, when given $(p + 1) \times (p + 1)$ autocorrelation matrix, the dimension of the noise subspace is equal to and is spanned by the eigenvector corresponding to the minimum eigenvalue. This eigenvector is orthogonal to each of the signal vector.

The frequency estimates may be determined by setting the frequencies equal to the angles of the roots of eigenfilter as shown below:

$$V_{\text{min}}(z) = \sum_{k=0}^{p} V_{\text{min}}(k) z^{-k}$$ (15)

Or the location of the peaks in the frequency estimation function as shown below:

$$\hat{P}_{\text{PHD}} e^{jw} = \frac{1}{|e^{H_v \text{min}}|^2}$$ (16)

where $V_{\text{min}}$ is the noise eigenvector and

$$e = [1 \quad e^{jw} \quad e^{j2w} \ldots \ldots \quad e^{j(M-1)w}]^T$$ (17)

The estimation can also be done in a coded form by the use of matlab to execute the coded algorithm to obtain the estimated frequencies based on the input data from the experiment. Generally, Pisarenko generate a function called “omegahat” which finds the Pisarenko frequency estimates of the signal in each column.

The input data should be filtered first to get rid of other frequencies or large variation due to noise and the data are executed to obtain the frequency estimates.

However, the technique has got its advantages and disadvantages as mentioned below:

Advantages:

➢ the technique is accurate for a single (complex) tone [28];

➢ it is very fast technique whereby the estimates it produces may be used to initialize other algorithm.
Disadvantages:

➢ it is not asymptotically efficient (as the input goes to infinity);
➢ it is statistically inefficiency.

3.4 Weighted linear predictor

This is one of the Weighted Phase Averaging frequency estimator’s technique which finds the weighted linear predictor frequency estimates of the signals in each column of the signal. Generally, the weighted linear predictor frequency estimate is given by the following equation;

\[
\hat{w}_0 = \text{arg} \left( \sum_{t=1}^{T-1} w_t z_t z_{t-1}^* \right),
\]

(18)

where \( w_t \) is a given window function, \( \text{Arg} \left( z \right) \) – phase of complex-valued \( z \)

As described above, there are different estimators which can be defined by the type of window function being used in the algorithm. The window functions that can be chosen to find the frequency estimator in weighted linear predictor are:

➢ Lank, Reed and Pollon window estimator;
➢ Lovell and Williamson window estimator;
➢ Clackson, Kootsooks and Quinn window estimator;
➢ Kay window estimator.

In this study, Kay window estimate will be used to analyze the output results from the data sets obtained from ring laser due to its computational simplicity compared to the rest of the window estimators above. Hence the weights of the Kay’s window estimators is given by the equation below:

\[
\hat{w}_t = \frac{6t(T - 1)}{T(T^2 - 1)};
\]

(19)

\( t = 1, \ldots, T - 1. \)

In addition, S. M. Kay developed an algorithm that calculates the frequency estimates of the signal that employ Kay’s window estimator. He develop a function which inputs the filtered data from the experiments and gives out the frequency estimates.

Then the frequencies is again calculated by the using equation (19) the same as in Pisarenko technique. The technique also has got advantages and disadvantages as outlined below:

Advantages:

➢ statistical efficient over a large region of parameter space;
➢ less computational intensive;
➢ computational efficient if the estimate can be computed in O(T) steps
Disadvantages;
➢ Clarkson, Kootsookos and Quinn [1994] have analyzed the performance of a class of weighted-phase frequency estimators, and have shown that such estimators are not asymptotically statistically efficient.

3.5 Hilbert transform

Hilbert transform is a linear operator that takes a function such as \( u(t) \) and produces another function i.e. \( H(u)(t) \) with the same domain. It is the technique that derives the analytic representation of a given signal; that means the signal \( u(t) \) is extended into the complex plane which satisfies the Cauchy-Riemann equations as shown below:

\[
\begin{align*}
\frac{\partial u}{\partial x} &= \frac{\partial v}{\partial y} ,
\frac{\partial u}{\partial y} &= -\frac{\partial v}{\partial x} .
\end{align*}
\]  

(20)  

(21)

Whereby \( u \) and \( v \) are the real and imaginary parts of a complex-valued function of a single complex number respectively.

Generally, Hilbert transform of a function \( g(t) \) is defined as:

\[
\mathcal{H}[g(t)] = g(t) \ast \frac{1}{\pi t} = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{g(\mathcal{T})}{t - \mathcal{T}} \, d\mathcal{T} = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{g(t - \mathcal{T})}{\mathcal{T}} \, d\mathcal{T}.
\]  

(22)

3.5.1 Basic properties of Hilbert transform

➢ It is clear from the definition of Hilbert transform of a time domain function that the Hilbert transform of a signal \( g(t) \) is another time-domain signal \( \hat{g}(t) \).

➢ The Hilbert transform is linear such that when \( a_1 \) and \( a_2 \) are arbitrary (complex) scalars and \( g_1(t) \) and \( g_2(t) \) are signals, then:

\[
[a_1 g_1(t) + a_2 g_2(t)]^* = a_1 \hat{g}_1(t) + a_2 \hat{g}_2(t).
\]  

(23)

➢ For any constant signal, the Hilbert transform of the constant signal \( g(t) \) is zero, that is
\[ \hat{g}(t) = 0. \] (24)

➢ If \( g(t) \) has Hilbert transform \( \hat{g}(t) \), then \( g(t - t_0) \) has Hilbert transform \( \hat{g}(t - t_0) \) and \( g(at) \) has Hilbert transform \( \text{sgn}(a)\hat{g}(at) \), where \( a \neq 0 \).

➢ The Hilbert transform behave nicely with respect to convolution as shown below:

\[
[g_1(t) * g_2(t)]^\wedge = \hat{g}_2(t) * g_1(t) = \hat{g}_1(t) * g_2(t). \] (25)

➢ The Hilbert transform of the derivative of the signal is the derivative of the Hilbert transform of that signal that is:

\[
\mathcal{H} \left[ \frac{d}{dt} (g(t)) \right] = \frac{d}{dt} \mathcal{H}[g(t)]. \] (26)

Hilbert transform in Matlab is useful in calculating the instantaneous attributes of the time series signal such as amplitude and frequency which are the amplitude of the complex Hilbert transform and the time rate of change of instantaneous phase angle respectively.

Essentially, the Hilbert Transform function complete the calculation in the following steps [10]:

➢ calculate the Fast Fourier Transform (FFT) of the input signal \( x_r \);
➢ all the frequencies that correspond to the interval \( -\pi < \omega < 0 \) are replaced by zeros;
➢ and finally the inverse of FFT is then calculated.

### 3.6 Hilbert Huang Transform (HHT)

All the fore mentioned techniques were developed for analyzing signals by considering them to be linear and stationary or nonlinear and stationary or linear and nonstationary. Generally, in a real world application the data are nonlinear and nonstationary which leads to the difficulties when it comes to analyze data in terms of frequencies, amplitudes, phase etc. by the use of traditional techniques mentioned earlier.

Considering the challenge, Norden E. Huang with his collaborators came out with a new approach called Hilbert-Huang Transform (HHT) for analyzing the nonlinear and nonstationary signals in most frequently real word signal processing problems.
The idea behind the technique is the decomposition of the signal referred to as the Empirical Mode Decomposition (EMD) into its Intrinsic Mode Functions (IMFs). The EMD is an adaptive filtering process whereby each time a monocomponent signal is filtered from the original signal in a progressive manner until all the frequency component has been separated leaving the residual signal [29].

Finally the frequency component of a separate signal is obtained by the application of Hilbert transform to the IMFs through Hilbert Spectral Analysis (HSA) method. Generally, using the Hilbert Huang Transform (HHT) a signal can be represented by the equation below:

\[ x(t) = \sum_{i=1}^{n} h_i + r, \]  

Where \(x(t)\) – time domain signal, \(h_i\) – intrinsic mode function of the signal and \(r\) – final residual signal without any oscillations.

To decompose a signal by HHT, the following procedures are considered:

- finding all the local maxima of the signal and determine the upper envelope \(U(t)\) by cubic-spline interpolation of the local maxima;
- determine the lower envelope \(L(t)\) in a similar manner as upper envelope but by using the local minima;
- obtain an Intrinsic Mode Function (IMF) by subtracting the mean of the upper and lower envelope from the signal as shown below;

\[ F_{IM} = X(t) - \left[ \frac{U(t) + L(t)}{2} \right]; \]  

- once the first IMF has been obtained, it is subtracted from the signal and the residual signal is considered to be the new signal then EMD is applied again and the process repeats until the residual signal contains no any oscillations.

Hilbert-Huang Transform has become more applicable due to its ability to analyze nonlinear and nonstationary signal as compared to other techniques. Some of the advantages of the HHT over the other techniques are as follows:

- it enables the signal analysis to avoid generating unphysical results such as spurious amplitudes at negative frequencies as seen from Hilbert Transform (HT);
- the technique is adaptive in nature that means; it avoids fixed limits of the bans covered by each Intrinsic Mode Functions (IMFs);
➢ it is more flexible compared to traditional techniques;
➢ the output from the HHT is easily interpreted.

However, the technique is still facing some challenges in its applications though some of them have been slightly controlled using an additive technique to the HHT. The following are the disadvantages of HHT:

➢ number of necessary Intrinsic Mode Functions (IMFs) are not known priori, since the process of decomposition is performed as an adaptive filtering process;
➢ possible constraints when distinguishing different components with near frequencies, though to some extent the problem has been reduced by the slightly improvement done based on the beating phenomenon of waves, in which the envelope of the superposition of two waves will be oscillating at the frequency difference of the two waves [30];
➢ empirical Mode Decomposition (EMD) is computationally expensive especially when the time series is long, it has a large frequency distribution and a high sample rate;
➢ there will be possible masking problems when high energy components are present in the signal as it will destruct the originality of the other lower energy components in the signal.
4 Results and discussion

Frequency estimation algorithm are used to estimate frequency of the varying output signal on the photodetector resulted from the Earth rotation with the variations imposed by seismic activities. The raw data that has been collected at a specified sampling rate are used as an input to the frequency estimation algorithm of which the end result will be the estimated frequency of the Earth rotation. Depending on the type of instruments and the primary application of the data collected one has to decide the sampling rate and frequency acquisition rate while processing raw data using the algorithms.

In this chapter, the results of the algorithms are mainly obtained on the raw data collected from the G-ring laser. This is because the G-ring laser so far is currently being used for seismological and geodesy applications as its performance surpass all the other instruments for the application thereof. However, for the further analysis of the algorithms, the raw data from C-II ring laser will also be processed using the algorithms though the instruments is currently inactive in the workstation.

In addition to that, further analysis of the algorithms when tested in different conditions will also be done specifically by varying the acquisition rate of the Sagnac frequency. Due to ambiguities and limitations associated with Hilbert Huang Transform (HHT) as discussed earlier and the large volume of data to be processed, HHT transform will not be included in the analysis of the outputs results of each algorithm unless in some point that requires its inclusion.

4.1 Results from G-ring laser data

Two data sets were used to obtain the results using the algorithms in which both data have the same Sagnac frequency because the Sagnac frequency is predetermined by the geometrical shape of the instruments which is the same for both case but their sampling rate were different. In the first case, the sampling rate of the raw data from the ring laser was 10 kHz collected for 600 sec and 348.5Hz as the Sagnac frequency. As stated earlier that the acquisition rate of the Sagnac frequency may vary due to the application of the data being processed.

Therefore, depending on the frequency content of the raw data, one has to choose the appropriate rate so that to be able to detect the frequency, that means the higher the frequency contents, the higher is the acquisition rate. But in this case, since the focus of research is to analyze the performance of different techniques, the acquisition rate is chosen to be 1Hz (1sec), which means after every 1sec, the Sagnac frequency needs to be estimated. However, for further analysis the acquisition rate will vary considering both local and teleseismic events with higher and lower frequency contents respectively.
The results of each algorithm when estimating the frequency are obtained using Matlab where by each algorithm is coded and run in Matlab to observe the output and finally comparing their performance by considering Autoregressive technique as the reference if things will work as expected especially on the outputs graphs. The outputs from Matlab for each algorithms is presented in the following figure 16 with the same length of time by zooming out a specified section on the figure for the purpose of observing a clear nature of the Sagnac frequency variations.

![Graphs of frequency variations](image)

Figure 16 (a) – AR(2), (b) – Quinn & Fernandes, (c) – Weighted linear phase predictor, (d) – Pisarenko, (e) – Hiilbert transform
As mentioned before, that when comparing the algorithms, Autoregressive is the reference one because the aim of the comparison is to find out the algorithm that will surpass the performance of AR (2). Therefore, following that the rest of the algorithms must conform first to AR (2) such that their frequency variations graph must resemble to that of AR (2) before other criteria such as processing time, deviation etc. to be considered.

Hence from the above observations, both of the technique does not match on their outputs with that of AR (2) as they contain oscillations on their outputs except for Hilbert transform which varies in a different ways not resemble to either of the techniques.

Moreover, when the deviations of Pisarenko and Hilbert transform are quite large as compared to the three techniques which seems at least to be equal. Because the deviation of AR (2), Phase and Quinn & Fernandes are nearly equal, they can be plotted in the same graph (Figure 17) to see their variations.

![Frequency deviation from the mean value](image)

**Figure 17 – AR (2), Quinn and Phase technique on the same plot**

From figure 17 it is clearly indicate that Quinn and Phase technique has the same oscillations though their amplitudes are different. But this has nothing to do with the comparison to AR (2) where their output should at least resemble to Autoregressive technique so that they can be compared from that point. Hence more data needs to be analyzed to observe the outputs of the techniques if they still behave same or otherwise.
Contrast to the first data set, in this case the sampling rate is 2000Hz which is low compared to the first set but the Sagnac frequency is the same because the same instrument was used. Also the volume of raw data is large and there are more than one set of data with some of them contains disturbances associated with an Earthquake. Therefore, the outputs of the algorithms will be considered for both seismic and non-seismic data in order to observe if there will be any inconsistence of the algorithms. The outputs from each of the algorithms are presented in figures 18 (a-e).

Figure 18 (a) – AR(2), (b) – Quinn & Fernandes, (c) – Weighted linear phase predictor, (d) – Pisarenko, (e) – Hilbert transform
Despite the fact that, the sampling rate and the volume of data processed being different, the four technique still does not resemble to the reference one. The oscillations are still there as seen in the first case while Hilbert transform still provide a unique variations. When the first three graphs with nearly equal deviation are plotted in the same graph as in the first case, Quinn and Phase technique are identical both in their oscillation character as well as their amplitudes as shown in figure 19.

![Frequency deviation from the mean value](image)

Figure 19 – AR (2), Quinn and Phase technique on the same plot for second G-ring laser data

### 4.2 Results from C-II ring laser data

The C-II ring laser is currently inactive as it has been replaced by G-ring laser due to its performance being good compared to C-II. Therefore, these data are also for observing the trend of these techniques if they will behave in a different way or the same and the observation might leads to some facts about the characteristics of the technique considering the previous observation when applied on the data from G-ring laser.

The difference here is on the Sagnac frequency, sampling rate and the geometrical shape of the instruments which is the vital factor on the determination of the Sagnac frequency as it is proportion to the area of the instrument. The predetermined C-II ring laser Sagnac frequency was 79.76 Hz, with the sampling
frequency of 1000 Hz and the acquisition rate of the Sagnac frequency is primarily considered to be 1Hz during the estimation by using the frequency estimation techniques.

Again, the outputs from each algorithms is obtained using Matlab software and their trends will also be compared to the previous one to see how they vary when the Sagnac frequency is changed due to the size of the instrument used as well as the sampling rate. The figure below presents the outputs graphs of each of the techniques.

![Graphs of different techniques](image)

Figure 20 (a) – AR(2), (b) – Quinn & Fernandes, (c) – Weighted linear phase predictor, (d) – Pisarenko, (e) – Hilbert transform
The first three graphs are nearly equal in their deviations, and in comparison they can be plotted in the same graph and observe their trend. Figure 21 presents the graphs for Autoregressive technique (AR (2)), Quinn and Fernandes as well Weighted phase techniques both on the same plot.

![Graph showing frequency deviation from the mean value for AR2, Quinn, and Phase techniques](image)

Figure 21 – AR (2), Quinn & Fernandes and Phase technique for C-II ring laser on the same plot

It is clear that both techniques in the above figure behave the same, it is from this observation that the comparison should then be done based on the aforementioned criteria when comparing the rest of the techniques with the reference technique. But this is not possible because in our current situation, all the other techniques yields their outputs with oscillations which does not reflects the real outputs characteristics as observed from the reference techniques.

Following these observations from G-ring laser and C-II ring laser, still there is no clarity on how these techniques except AR (2) does not reflects the real characteristic in their outputs graphs. Therefore further analysis on the performance of the techniques needs to be done in order to know the reason behind for them to deviate from yielding the expected outputs graph of frequency variations which resembles to Autoregressive AR (2) technique.

Knowing the causes of the oscillation will enhance the suggestions of the possible ways to get rid of them for the purpose of comparing the techniques with the reference one because the comparison cannot be done until the outputs of all algorithms reflects the reality on their variations.
4.3 Further analysis of the algorithms based on oscillations

The analysis is primarily based on finding the reasonable facts and causes of the oscillations resulted on the outputs of the techniques as observed above. It is done by considering how the oscillations from each technique relates in terms of magnitudes and variations with the others while varying the acquisition rate of the Sagnac frequency. This will provide preliminary reason of the oscillations and way out for the solution. The analysis is done using the raw data from G-ring laser and C-II ring laser with different Sagnac frequency and sampling rate.

4.3.1 Analysis of oscillations on G-ring laser data

Considering the fact that, all the analysis were done based on the same frequency acquisition rate which was 1Hz for both G-ring laser and C-II ring laser data, but that value of the acquisition rate was not practically chosen to be the only value to acquire the Sagnac frequency.

In reality, the acquisition rate as stated earlier is determined by the range of frequencies to be detected by the ring laser whereby if the frequency contents of the output data with the exclusion of the Sagnac frequency is high (which might reach up to 10 Hz) and mostly in the areas where there is the local seismic activities, then acquisition rate is required to be high (up to 20 Hz or 0.05 sec) which is capable of detecting these high frequency components.

On the other hand, if the frequency contents is not as large as in the case of local seismic activities areas (might be up to 0.03 Hz), the acquisition rate is not highly recommended to be higher as compared to the first case. This is usually recommended for teleseismic data whereby the frequency contents is very low. Based on the previous analysis, the acquisition rate was considered to be low (1 Hz), which is mostly applicable for teleseismic events and normal Earth rotation rate monitoring. Therefore, for further and detail analysis aiming at comparing the algorithms, the consideration of the two cases should be taken into account.

In the first case which is mainly concern with low frequency contents of the output data, the results from all the techniques excluding the reference one indicates the deviation from the reality. But this should not be considered as the final conclusion, the second case which is for high frequency contents on the output data is also analyzed to observe if still there will be discrepancies between the reference technique (AR (2)) and the rest of the algorithms specifically the oscillations as seen in the previous analysis.

In this case the outputs of each algorithms will be obtained by changing the acquisition rate of the Sagnac frequency while keeping constant Sagnac frequency and sampling rate. The variations of acquisition frequency will be in the range of
0.3 Hz (3 sec) \leq f_{acq} \leq 20 Hz (0.05 sec) which covers both low and high frequency contents of the raw data from large ring laser.

From these results we shall have reasonable facts about the characteristics of these techniques in relation to the Autoregressive technique. Figure 26 (a-d) and 27 (a-d) represents the outputs graphs for raw data with 10000 Hz sampling rate when the acquisition rate of Sagnac frequency has been changed to 20Hz which is equivalent to 0.05sec, and 0.5Hz equivalent to 2sec respectively.

This means for every 0.05sec or 2sec, the frequency has to be estimated by the algorithms. In this analysis the figures indicates the time spent by each algorithms while estimating the Sagnac frequency, this time is referred to as Elapsed Time (ET), also the standard deviation (STD) of each algorithms as well as the oscillations frequency which is computed within the algorithms if it has.

Figure 22 (a) – AR(2), (b) – Quinn & Fernandes, (c) – Weighted linear phase predictor, (d) – Pisarenko
Figure 23 (a) – AR(2), (b) – Quinn & Fernandes, (c) – Weighted linear phase predictor, (d) – Pisarenko

As seen from figure 23, in all cases except for weighted phase, they still giving out oscillations in their outputs though the frequency of oscillation changes as the acquisition rate changes and in all algorithms the oscillation frequency in each case is the same. But these observations are for only two cases in changing the acquisition rate.

To summarize all the acquisition rate with their output characteristics, the table 3 presents the acquisition rate and oscillation frequency for each algorithms based on the data sample above. In each case as seen in the table, the oscillation frequency are the same for every algorithms and the trends shows that at the beginning the oscillations frequency goes on decreasing as the acquisition rate increases though at some point the oscillations frequency increases.
On the other hand, for raw data with 2000 Hz sampling rate, the analysis is the same as in the first case where both high and low frequency contents acquisition rate were taken into account. The difference here is only on the sampling rate and the volume of data being process.

The variation of acquisition rate of the Sagnac frequency is the same as in the first case in order to observe the trend whether they will have different oscillation frequency and from there we can be able to establish a reasonable facts about the oscillation behavior.

The following figures 24(a-d) and 25 (a-d) represents the outputs graphs for each algorithms when the acquisition rate is 20Hz (0.05sec)) specifically for the case if there will be high frequency contents to be detected and 0.5Hz (2sec) respectively for the low frequency contents of the raw data from ring laser.

For these two acquisition rate, the oscillation frequency in each case for both algorithms are the same as what observed in the first case with 10000 Hz sampling rate. For the remaining variation of the acquisition rate, table 4 below summarizes the oscillation frequency observed for each of the three algorithms. In the table it is again resemble to what were observed in the previous case where by at the first points the oscillation frequency goes on decreasing while acquisition rate increases though at the mid of points the oscillation frequency increase but in a very small amount.

Nevertheless, the raw data processed above were both taken from the same instrument (G-ring laser) as explained earlier, but according to the available data,
also the C-II ring laser data needs to be processed in order to see if there will be any new observations aside from what has been observed so far in the previous data analysis. Despite the fact that the instrument is no longer used for the purpose of monitoring the Earth rotation as it has been replaced by G-ring laser, but at least will provide some preliminary information and helpful for the solution of the problem of oscillation that hinder further comparison of the techniques.

The analysis of the data from C-II ring laser is done on the next subsection in which all cases such as high frequency contents acquisition rate as well as low frequency content acquisition rate are considered same as what is done in the previous case of G-ring laser data.

Figure 24 (a) – AR(2), (b) – Quinn & Fernandes, (c) – Weighted linear phase predictor, (d) – Pisarenko
Figure 25 (a) – AR(2), (b) – Quinn & Fernandes, (c) – Weighted linear phase predictor, (d) – Pisarenko

Table 4 – Acquisition rate and oscillation frequency of the output graphs for 2000Hz sampling rate on G-ring laser

<table>
<thead>
<tr>
<th>Acquisition time (sec)</th>
<th>Quinn &amp; Fernandes (Hz)</th>
<th>Weighted Phase (Hz)</th>
<th>Pisarenko (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0.08</td>
<td>2.97</td>
<td>2.97</td>
<td>2.97</td>
</tr>
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<td>2.97</td>
<td>2.97</td>
<td>2.97</td>
</tr>
<tr>
<td>0.2</td>
<td>2.03</td>
<td>2.03</td>
<td>2.03</td>
</tr>
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<td>0</td>
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<tr>
<td>3</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>
4.3.2 Analysis of oscillations on C-II ring laser data

The two cases above were taken from the same instrument at different time with their Sagnac frequency being the same while sampling rate and volume of registered data in the photodiode in each case is different. Regardless of their difference, still the outputs from each algorithms was seemed to contain the same oscillation behavior depending on the acquisition rate which was varied each time and processed in a given algorithms at a time.

In this case, contrast to the previous one, the instrument is different i.e. the scale factor is changed, this leads to the changing of the Sagnac frequency as well as sampling rate which is 1000Hz, while the Sagnac frequency was 79.76Hz. Despite the fact that the instruments is currently inactive at the site, but the output results for each algorithm will provide necessary information on the dependence of the oscillation behavior whether it is independent of the instrument or otherwise. The following figures 30 (a-d) and 31 (a-d) presents the frequency-time graph for acquisition rate of 20Hz (0.05sec) and 0.5Hz (2sec) respectively for C-II ring laser.

Figure 26 (a) – AR(2), (b) – Quinn & Fernandes, (c) – Weighted linear phase predictor, (d) – Pisarenko
Also in this case, the acquisition rate of Sagnac frequency is varied same as in the G-ring laser aiming at observing the outputs graphs with or without oscillations. Table 5 summarizes the outputs with their oscillation frequency if the oscillation is contained in the output graph.

Generally, the analysis on both G-ring laser and C-II ring laser reveals that the algorithms outputs the graphs with wiggles/oscillation though in C-II ring laser there is a bit of differences on the oscillation compared to those in G-ring laser but some of them are the same.

This observation leads to an ambiguous specifically on what brought about these oscillations which were observed to be in both cases regardless of the different instrument being used. In that manner we steel need to analyze the real data inorder to have a clear and reasonable fact about this nature and performance of the algorithms.
Table 5 – Acquisition rate and oscillation frequency of the output graphs for C-II ring laser with 1000Hz sampling rate

<table>
<thead>
<tr>
<th>Acquisition time(sec)</th>
<th>Quinn &amp; Fernandes (Hz)</th>
<th>Weighted Phase (Hz)</th>
<th>Pisarenko (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.47</td>
<td>0</td>
<td>0.47</td>
</tr>
<tr>
<td>0.08</td>
<td>2.97</td>
<td>2.92</td>
<td>2.97</td>
</tr>
<tr>
<td>0.1</td>
<td>0.47</td>
<td>0</td>
<td>0.47</td>
</tr>
<tr>
<td>0.2</td>
<td>0.47</td>
<td>0</td>
<td>0.47</td>
</tr>
<tr>
<td>0.4</td>
<td>0.47</td>
<td>0.4</td>
<td>0.47</td>
</tr>
<tr>
<td>0.6</td>
<td>0.46</td>
<td>0.4</td>
<td>0.47</td>
</tr>
<tr>
<td>0.8</td>
<td>0.3</td>
<td>0</td>
<td>0.47</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.44</td>
</tr>
<tr>
<td>1.5</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

4.4 Power Spectral Density (PSD) of raw data

Aside from the acquisition rate of the Sagnac frequency being varied, the other means of analyzing the output data from the photodiode is by examining the frequency contents of the useful signal. When processing the raw data from ring laser, the main focus is to have signal which carries Sagnac frequency while the rest of the information are treated to be noise that requires to be filtered out inorder to remain with the useful signal containing Sagnac frequency. In this case the power spectral density is determined in two aspects such as the normal PSD for raw data and the PSD when the signal is decomposed by the application of Hilbert Huang transform.

4.4.1 Power spectral density for undecomposed signal

The analysis of the frequency contents here is done by establishing the Power Spectral Density (PSD) of the raw data after being filtered using a specified filter. The Power Spectral Density of the raw data for both G-ring laser and C-II ring laser is presented in figures 28 - 30. From these figures we shall be able to observe if there will be any side band which correlates with any of the oscillation frequency observed in the previous analysis of G-ring laser as well as C-II ring laser.
Figure 28 – Power Spectral Density (PSD) for G-ring laser data with 10 kHz sampling rate

Figure 29 – Power Spectral Density (PSD) for G-ring laser data with 2 kHz sampling rate
The power spectral density for the first two graphs of G-ring laser contains neither sideband nor frequency components other than the actual frequency of the input signal (Sagnac frequency) while on the other hand C-II ring laser Power Spectral Density contains sideband which is the indication of the modulation on the Sagnac frequency. This modulation of the frequency is mainly concerned with the Earthquake which happened during the time when C-II ring laser was running.

But this modulation has nothing to do with the observed oscillations that the algorithms has on their outputs because we were expecting to see the frequency components which is equal or approximately equal to the observed frequency of oscillations as analyzed on the above tables.

### 4.4.2 Power spectral density for decomposed signal

The analysis of the input signal can also be done by decomposing the signal into its frequency components starting with the high frequency component which is the carrier to the lower one and thereafter, the analysis of each component is done but in our case the first component will be our interest as it carries the Sagnac frequency.

This can be done by Hilbert Huang Transform (HHT) which is an improvement of Hilbert transform as explained in detail in chapter 3. The following figures 31 – 33, presents the PSD for both G-ring laser and C-II ring laser after
decomposing the signal into its frequency contents as consider high frequency content which carries Sagnac frequency.

Figure 31 – Power Spectral Density (PSD) for G-ring lase with 10k Hz sampling rate when Hilbert Huang transform is applied first to the data

Figure 32 – Power Spectral Density (PSD) for G-ring lase with 2 kHz sampling rate when Hilbert Huang transform is applied first to the data
The PSD of the decomposed output signal by Hilbert Huang Transform (HHT) above contains neither sideband nor frequency components which relates to the frequency of oscillations as listed in the previous tables. So far, all that has been done aiming at analyzing the oscillation behavior of the three techniques does not provide any clarity on the causes of the oscillations whether is the intrinsic factors of the algorithms or extrinsic factors which relates to the instrument itself and its addition components to which all together produce the output signal.

Following this, the final remarks has to be made by considering both the instrument and the algorithms pointing out the relevant facts that might have been the main source of the oscillation and the possibilities on what should be done in the meantime or in the future work.

4.5 Analysis based on Hilbert transform

The analysis above is done by considering the oscillation behavior that has revealed in the three algorithms, but in the case of Hilbert transform (HT), the outputs results contains no any oscillations but still does not match with the output graphs obtained from Autoregressive technique which is considered to be the reference technique. This prompted more details analysis of the observed output.
from Hilbert transform inorder to have reasonable facts on what makes the algorithms to behave like that way.

As observed in the previous case, the variation of acquisition rate which were in small proportion did not have a significant effect on the output of the Hilbert Transform (HT) specifically in the analysis of the real data form both G-ring laser and C-II ring laser. Therefore, the analysis of the Hilbert transform requires other means of analyzing its output aside from varying the acquisition rate.

Generally, Hilbert transform as explained in chapter 3, works by decomposing the signal into two parts which are real and imaginary parts, the real part is the same as the signal but imaginary parts contains the information of phase and amplitude of the signal. This part is of more crucial when computing the instantaneous frequency of the signal is the main goal.

Hence, the analysis here is mainly concerned with the computation of the real and imaginary part of the signal that is how Hilbert Transform should be applied to the raw data from the ring laser.

Hilbert Transform in the previous analysis was applied in a sample wise which means the real and imaginary part of the signal is computed based on the sampling rate of the signal when processed by the algorithms. Therefore, every set of data collected at a given time according to the sample rate, has its real and imaginary part for computing the instantaneous frequency.

But in this analysis we need to observe what if Hilbert Transform will be computed first for all the available raw data and then followed by the computation of instantaneous frequency according to the specified sampling rate of the raw data. In this case contrast to the previous, the Hilbert transform is applied to the total volume of the data without dividing the raw data into beans and then after obtaining the instantaneous amplitudes and phase, then the computation of Sagnac frequency is done within beans of data.

This act of computing Hilbert transform first for all data is not applicable in our case but for the sake of understanding this s done purposefully to see what will be the difference aiming at providing a good conclusion based on Hilbert transform.

In comparison with the outputs that has been observed before, the following figures 34 – 36, presents the outputs graphs of G-ring laser for each case and that of C-II ring laser when the Hilbert Transform is applied first for all the available raw data followed by computing instantaneous frequency of in a sample wise.
Figure 34 – Hilbert Transform when computed at once for all data from G-ring laser of 10000 Hz sampling rate

Figure 35 – Hilbert Transform when computed at once for all data from G-ring laser of 2000 Hz sampling rate
Comparing to the previous results, it is clearly that Hilbert in this case perform even better than Autoregressive (AR (2)) technique specifically on the duration of computation and standard deviation. But according to the requirement of our search is to have a technique which is capable of producing the results in near real time and not post processing, because in AR (2) the computation is done in a near real time.

But when Hilbert transform is computed for all data first then instantaneous frequency in sample wise that means it is the post processing which is not reflecting the main goal of the search. In that manner this observation does not benefit or fulfill the aim of the finding and should not be taken into account.

Nevertheless, this observation provide to us a preliminary reasonable facts about the volume of the data being processed at a specific time by the Hilbert Transform that is, the volume of the raw data to computed determines the quality of the instantaneous frequency, whereby the larger the volume of the data the smaller deviations of the instantaneous frequency computed.

This prompted us to compute the instantaneous frequency in a sample wise but in this case the volume of the data being processed at a specific time is made to be large by increasing the acquisition rate of the instantaneous frequency to a large extent and not like in the previous variation which were done in a very small amount.
Considering that, the volume of the data to be processed is required to be large, the raw data from only G-ring laser with 2000 Hz sampling rate will be used as the volume is quite enough to obtain large amount of estimated Sagnac frequency. The other data are not large in volume to the extent that when Sagnac frequency is estimated it will be large too. The figures (37 – 40) presents the comparison of Hilbert when computed with normal acquisition rate and when the volume of the bin is increased to a large extent.

![Graph](image)

**Figure 37 – Hilbert transform when the acquisition rate is 20 Hz (0.05sec)**

![Graph](image)

**Figure 38 – Hilbert Transform when the acquisition rate is 1 Hz (1 sec)**
The two graphs are mainly done by considering the two cases when the frequency content is high which requires short period (high frequency) of time when acquiring the frequency from the raw data and also for low frequency contents which needs not high rate of acquisition compared to when the frequency contents is high. On the other hand when the volume of the data is increased to the large extent and estimate the Sagnac frequency, the results are presented on the figures 39 and 40.

Figure 39 – Hilbert transform when the acquisition rate is 0.02 Hz (50 sec)

Figure 40 – Hilbert transform when the acquisition rate is 0.004 Hz (250 sec)
Comparing the two figures, 39 and 40 and the previous figures 37 and 38, it is clearly pointed out that Hilbert transform has a significant improvement in both the nature of the graphs and the standard deviation when the number of sample in increased to the large extent. Though the resulted graphs are not yet resemble to the reference one, at least it shows some improvement on the way it propagates and it is clearly that when the transform is applied to all data, the results are quite the same to that of the AR (2) as observed in the previous analysis.

Hence, this provide clear understanding that the Hilbert transform is usually fits for large sample of data to be processed otherwise the results will deviate from the expected one.
5 Safety

This is an addition chapter to the project which normally contains a significant information about the project based on what has been done. Normally the chapter is devoted to give out an information of how the research/project has been developed, the guidance on how to take care of the developed project if the project was aimed to produce something at the end, usability of the project etc.

The safety issues regarding any project is established based on the international standards (ISO) which contains all the necessary information that has to be taken into account when preparing safety part of a given project or activity.

In a general overview, safety is the an act/procedure/means of doing something in a manner of that reduces the risk of accident by means of impact, fracture, shattering or in a fire or it is the state of being protected against physical, social, occupational, psychological and emotional. This is normally the first and very important part to be taken into account before the use or implementation of anything that human interacts with or to some extent with human being.

5.1 Types of safety

Normally, safety is categorized into four categories depending on the situations or the intended user of the product or anything that human is interacted with. These categories are explained as follows:

➢ Normative safety.

This type of safety is usually achieved when a product or design meets applicable standards and practices for design and construction or manufacture, regardless of the product's actual safety history. It is a term used to describe the designs or product that has developed and meets the applicable standards.

➢ Substantive safety.

Substantive or objective safety occurs when the real-world safety history is favorable, whether or not standards are met.

➢ Perceiving safety.

This is sometime referred to as subjective safety refers to the users' level of comfort and perception of risk, without consideration of standards or safety history. For example, traffic signals are perceived as safe, yet under some circumstances, they can increase traffic crashes at an intersection. Traffic roundabouts have a generally favorable safety record [31] yet often make drivers nervous.
Low perceived safety can have costs. For example, if an incident that relates to flight accident or plane hijacking it might cause some if not many of the people chose to drive rather than fly, despite the fact that, even counting terrorist attacks, flying is safer than driving. Perceived risk discourages people from walking and bicycling for transportation, enjoyment or exercise, even though the health benefits outweigh the risk of injury [32].

➢ Security.

It is also referred to as social safety or public safety, this safety normally addresses the risk of harm due to intentional criminal acts such as assault, burglary or vandalism. Because of the moral issues involved, security is of higher importance to many people than substantive safety. For example, a death due to murder is considered worse than a death in a car crash, even though in many countries, traffic deaths are more common than homicides.

5.2 Safety measures

These are the activities and precautions taken to improve safety for the purpose of reducing the risk related to human health. This is a significant part that is required in any activities that provide the user or those who are involved in the situation with the instructions or precaution to be taken for maintaining the safety of a given place and the surrounding. There are different categories of safety measures that depends on the application and the nature of the product, systems or design. Some of the safety measures that are common are presented as follows:

➢ Instruction manual.

After the product being design or systems, the designer is required to provide the information of the designed system or product specifically issues regarding the use and how the product or system should be maintained aiming at increasing the safety and reliability of the system or product.

Therefore it meant to inform users that before doing anything on the product he/she must study keenly the information that is in the manual or at any point which needs more clarification the instruction manual needs to be revised.

It is an instructional book that is supplied with almost all technologically advanced consumer products such as vehicles, home appliances and computer peripherals. Information contained in the instruction manual typically includes:

a) safety instructions; for liability reasons these can be extensive, often including warnings against performing operations that are ill-advised for product longevity or overall user safety reasons;
b) programming instructions; for microprocessor controlled products such as VCRs, programmable calculators, and synthesizers;

c) regulatory code compliance information; for example with respect to safety or electromagnetic interference;

d) setup instructions; for devices that keep track of time or which maintain user accessible state etc.;

➢ root cause analysis (RCA).

This is a method of problem solving used for identifying the root causes of faults or problems. A factor is considered a root cause if removal thereof from the problem-fault-sequence prevents the final undesirable event from recurring; whereas a causal factor is one that affects an event's outcome, but is not a root cause. Though removing a causal factor can benefit an outcome, it does not prevent its recurrence with certainty.

As an example of identifying root cause analysis, imagine a fictional segment of students who received poor testing scores. After initial investigation, it was verified that students taking tests in the final period of the school day got lower scores. Further investigation revealed that late in the day, the students lacked ability to focus. Even further investigation revealed that the reason for the lack of focus was hunger. So, the root cause of the poor testing scores was hunger, remedied by moving the testing time too soon after lunch.

RCA is applied to methodically identify and correct the root causes of events, rather than to simply address the symptomatic result. Focusing correction on root causes has the goal of entirely preventing problem recurrence. Conversely, RCFA (Root Cause Failure Analysis) recognizes that complete prevention of recurrence by one corrective action is not always possible.

It is typically used as a reactive method of identifying event(s) causes, revealing problems and solving them. Analysis is done after an event has occurred. Insights in RCA make it potentially useful as a preemptive method. In that event, RCA can be used to forecast or predict probable events even before they occur. While one follows the other, RCA is a completely separate process to incident management.

Generally root cause analysis (RCA) has been classified into different classes as mention below:

a) safety-based RCA arose from the fields of accident analysis and occupational safety and health;

b) production-based RCA has roots in the field of quality control for industrial manufacturing;
c) process-based RCA, a follow-on to production-based RCA, broadens the scope of RCA to include business processes;

d) failure-based RCA originates in the practice of failure analysis as employed in engineering and maintenance;

e) systems-based RCA has emerged as an amalgam of the preceding schools, incorporating elements from other fields such as change management, risk management and systems analysis.

➢ Internet safety

Internet safety is in general referred to as web safety or online safety. It is the knowledge of maximizing the user's personal safety and security risks to private information and property associated with using the internet, and the self-protection from computer crime in general. As the number of internet users continues to grow worldwide, internets, governments and organizations have expressed concerns about the safety of children using the Internet.

Safer Internet Day is celebrated worldwide in February to raise awareness about internet safety. In the UK the Get Safe Online campaign has received sponsorship from government agency Serious Organized Crime Agency (SOCA) and major Internet companies such as Microsoft and eBay.

Sensitive information such as personal information and identity, passwords are often associated with personal property (for example, bank accounts) and privacy and may present security concerns if leaked. Unauthorized access and usage of private information may result in consequence such as identity theft, as well as theft of property. Common causes of information security breaches include, phishing, internet scams and malware.

The growth of the internet gave rise to many important services accessible to anyone with a connection. One of these important services is digital communication. While this service allowed us to communicate with others through the internet, this also allowed the communication with malicious users. While malicious users often use the internet for personal gain, this may not be limited to financial/material gain. This is especially a concern to parents and children, as children are often targets of these malicious users. Common threats to personal safety include:

✓ Cyberstalking.

This is the use of the Internet or other electronic means to stalk or harass an individual, a group of individuals, or an organization. It may include the making of false accusations or statements of fact (as in defamation), monitoring, making threats, identity theft, damage to data or equipment, the solicitation of minors for sex, or gathering information that may be used to harass. According to a study
conducted by Baum et al. (2009), the rate of assault through electronic means such as e-mail or instant messaging was over one in four out of all stalking victims in the study [33].

✓ Cyberbullying.

This is an attack upon an individual or group through the use of electronic means such as instant messaging, social media, e-mail and other forms of online communication with the intent to abuse, intimidate, or overpower. In a 2012 study of over 11,925 students in the United States, it was indicated that 23% of adolescents reported being a victim of cyber bullying, 30% of which reported experiencing suicidal behavior [34].

➢ Software safety.

Software system safety, is an element of the total safety and software development program, cannot be allowed to function independently of the total effort. Both simple and highly integrated multiple systems are experiencing an extraordinary growth in the use of computers and software to monitor and/or control safety-critical subsystems or functions. A software specification error, design flaw, or the lack of generic safety-critical requirements can contribute to or cause a system failure or erroneous human decision.

To achieve an acceptable level of safety for software used in critical applications, software system safety engineering must be given primary emphasis early in the requirements definition and system conceptual design process. Safety-critical software must then receive continuous management emphasis and engineering analysis throughout the development and operational lifecycles of the system.

Software system safety is directly related to the more critical design aspects and safety attributes in software and system functionality, whereas software quality attributes are inherently different and require standard scrutiny and development rigor. Level of Rigor (LOR) is a graded approach to software quality and software design assurance as a pre-requisite that a suitable software process is followed for confidence.

LOR concepts and standards such as DO-178C are NOT a substitute for software safety. Software safety per IEEE STD-1228 and MIL-STD-882E focuses on ensuring explicit safety requirements are met and verified using functional approaches from a safety requirements analysis and test perspective.
5.3 Safety issue based on the project

Generally, the project is devoted to the analysis of different frequency estimation algorithms aiming at obtaining the one with the capability of estimating frequency in a real time or near real time. The estimated frequency is done based on the real raw data from the large ring laser which is mainly used for monitoring the Earth rotation. The estimated frequency is the one which is used to compute the Earth rotation rate at a specific time.

During computation of the frequency which is to a Sagnac frequency, Matlab software is used where by each algorithms has got its own function which is developed for the purpose of estimating frequency and executed in Matlab. Therefore, based on the scope of the project, the main considering will be on the safety issues regarding computers as it is used to carry out all the tasks for the project, also the usability of software in which on my case the usability of Matlab will be taken into account as well the usability of the developed programs that has been used to estimate the Sagnac frequency in each algorithms.

Therefore, considering what has been in the project, basically the main issues regarding safety will be focuses on the two main parts. Namely, usability of Matlab and the programs that has been developed for the purpose of estimating the Sagnac frequency of the raw signal from large ring laser.

5.3.1 Usability of Matlab

MATLAB is an abbreviation of the name Matrix Laboratory. It is a multi-paradigm numerical computing environment and fourth-generation programming language. A proprietary programming language developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python.

Although MATLAB is intended primarily for numerical computing, an optional toolbox uses the MuPAD symbolic engine, allowing access to symbolic computing abilities. An additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamic and embedded systems. Its users come from different fields such as engineering, science and economics.

Since Matlab is a software it is always used with the help of a computer, that means it has to be installed on the computer when requires to be used for a specific
task. The installation of Matlab requires an individual to have license to use the software. It is a proprietary product of MathWorks, so users are subject to vendor lock-in. Although MATLAB Builder products can deploy MATLAB functions as library files which can be used with .NET or Java application building environment, future development will still be tied to the MATLAB language.

Each toolbox is purchased separately. If an evaluation license is requested, the MathWorks sales department requires detailed information about the project for which MATLAB is to be evaluated. If granted, the evaluation license is valid for two to four weeks. A student version of MATLAB is available as is a home-use license for MATLAB, Simulink, and a subset of MathWorks Toolboxes at substantially reduced prices.

Usability of Matlab is a general consideration of the how Matlab has been able to deliver the required results based on the project. Since Matlab has its limitations, the usability is the basic criteria to be considered for carrying out the task. According to ISO 9241-210:2010, 2.13, the usability has been described as extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.

Following the ISO requirements on the usability of a given software, specifically on this project Matlab, there is an important features of the Matlab that needs to be considered when assessing its usability based on the intended task. These features will help to provide an information to the user if he/she will attain the final results otherwise there will be no need of using the software if it won’t provide the final results.

The following features of Matlab are significant when carrying out this project.

➢ Variables

Variables are defined using the assignment operator, =. MATLAB is a weakly typed programming language because types are implicitly converted. It is an inferred typed language because variables can be assigned without declaring their type, except if they are to be treated as symbolic objects, and that their type can change. Values can come from constants, from computation involving values of other variables, or from the output of a function. Therefore in this case, the variables must be identified using the specified syntax otherwise there will difficult to reach to the final answer.

➢ Structures

MATLAB has structure data types. Since all variables in MATLAB are arrays, a more adequate name is "structure array", where each element of the array
has the same field names. In addition, MATLAB supports dynamic field names. Unfortunately, MATLAB JIT does not support MATLAB structures, therefore just a simple bundling of various variables into a structure will come at a cost.

➢ Functions

When creating a MATLAB function, the name of the file should match the name of the first function in the file. Valid function names begin with an alphabetic character, and can contain letters, numbers, or underscores. Functions are also often case sensitive.

➢ Function handles

MATLAB supports elements of lambda calculus by introducing function handles, or function references, which are implemented either in .m files or anonymous nested functions. Since in this project the fundamental issues to be considered is the functions because throughout the task the main activities will be based on the implemented functions and how to use the functions in the Matlab, hence having an assurance of the compatibility of the available functions with Matlab is very crucial.

➢ Vectors and matrices

Considering the project, sometimes the raw data from the ring laser might be in terms of matrix, this prompt the user to know how to upload the required raw or column for the purpose of computing the required value. Generally, the matrices can be defined by separating the elements of a row with blank space or comma and using a semicolon to terminate each row. The list of elements should be surrounded by square brackets: [ ]. Parentheses: () are used to access elements and subarrays.

Most MATLAB functions can accept matrices and will apply themselves to each element. For example, mod (2*J, n) will multiply every element in "J" by 2, and then reduce each element modulo "n". MATLAB does include standard "for" and "while" loops, but (as in other similar applications such as R), using the vectorized notation often produces code that is faster to execute. This code, excerpted from the function magic.m, creates a magic square M for odd values of n.

Although Matlab has been chosen for the task, the consideration also must be put on the volume of the data to be processed. Based on the project, the data to be analysed were very large in volume for example data from large ring laser were nearly two hundred millions. In this case, Matlab processor is not capable of carrying out the task of estimating Sagnac frequency because it was running out of memory. Hence for this case the requirements was to upload a volume of the data that is within the capability of Matlab otherwise nothing will be produced by the software.
5.3.2 Usability of the program

As stated early that, the estimation of the Sagnac frequency is carried out by the implementation of functions of the algorithms and it is to be executed in the Matlab. Functions itself is not enough because it is developed for a specific purpose and no any other additional information. That means and there must be addition programs to which the function is called so that the estimation of the required frequency to be done. Therefore, a user must be able to implement his/her own code for the purpose of calling the specified function and executing the programs to obtain the results.

According to the ISO 9241-129:2010(E) clause 9.2.6 which requires the software to be able to prevent configuration actions from changing settings which would prevent access to the basic functions requires for the completion of user’s task, these functions that has been developed for carrying out the task are not supposed to be changed, the only thing is to call them within a program without changing the contents of the function itself. If for example the function has been varies Matlab itself will give out the error and nothing will be executed because the function is changed.

MATLAB supports object-oriented programming including classes, inheritance, virtual dispatch, packages, pass-by-value semantics, and pass-by-reference semantics. However, the syntax and calling conventions are significantly different from other languages. MATLAB has value classes and reference classes, depending on whether the class has handle as a super-class or not.

Also MATLAB supports developing applications with graphical user interface (GUI) features. MATLAB includes GUIDE for graphically designing GUIs. It also has tightly integrated graph-plotting features. For example, the function plot can be used to produce a graph from two vectors x and y. Since the programming part endup with the results and some features example graphs.

International Standard organization (ISO) also recommended that there must fulfillment of the requirements the usability of individualization of results and features. This has been specified by ISO 9241-129:2010(E) clause 7.5.1 and 7.5.2 which says; system-initiated individualization should not result in a foreseeable decrease in the overall usability of the user interface for the intended user and the individualization features available to the user should have a high level of usability respectively. Based on the individualization of features it is important to pay attention on the following issues:
➢ it is important that individualization features have a high level of usability or it is likely that they will not be used;
➢ usability of individualization features can be increased by allowing systems to share a user's individualization settings;
➢ it is desirable that individualization features do not interfere with assistive technologies and do not reduce the level of accessibility.

Considering the nature of the task to be carried out, the designed programs for estimating Sagnac frequency requires to be flexible in the sense that, during the analysis of the algorithms the programs can be varied to estimate different kind of data sample which depends on the acquisition rate of the sample. Therefore, the implemented code is to take into account the flexibility issue otherwise the task will consume much time to be completed.
Conclusion

The report is generally composed of introduction describing the overview of the Earth rotation and how monitoring is done by the use of different techniques such as Very Long Baseline Interferometry (VLBI) and large ring laser gyroscope. More specifically the effort as mainly on the ring laser as it is currently used for such purpose. Using large ring laser, monitoring is done by estimating the Sagnac frequency which is then used for obtaining the Earth rotation when the instrument is operated. The estimation is currently done by Autoregressive technique, though there are other counterpart techniques such as Quinn & Fernandes, Weighted Linear phase Predictor and Pisarenko that were analyzed for finding the best of all.

The analysis were done based on real data from G-ring laser and C-II ring laser and the results shows the three techniques Quinn & Fernandes, Weighted phase linear predictor and Pisarenko contains oscillations in their outputs which does not reflect the reality when compared to the AR (2). On the other hand Hilbert transform does not fits for the application as it requires large number of sample for precise estimation.

The oscillations on the output might be related to the instrument itself as well as the algorithms because in the previous analysis it was revealed that there is no way we can rely only on the instrument or algorithms as they both seems to have effect on the output results, therefore both of them are considered.

Normally, during the process of acquiring data from large ring laser the discrete signal is sampled by selecting the appropriate sampling frequency depending on the data to be collected. This is done by the logger which is the additional component to the ring laser during performance. Logger are not the same, there are different kind of logger to be used for different purpose and therefore this might probably be the cause of the oscillations on their outputs graphs though this is very minor to be taken into account.

On the other hand, algorithms are also considered to be the source of oscillations because in most cases especially when the acquisition rate varies, the algorithms gives out the same value of oscillation frequency. Therefore, this might have been resulted from the way these algorithms have been coded, because the results is obtained after being processed using Matlab function developed for the purpose thereof.

Considering all these observations, the main conclusion is based on two cases as explained below.

It is clearly that so far based on the real data sets, acquisition rate and sampling frequency, still the Autoregressive technique which is currently used for the purpose,
remains to be the most efficient and effective technique compared to others that have been analysed. This is because the three techniques outputs their results with oscillations which does not reflect the reality and Hilbert transform fits for large volume of the data that is to be processed in a real time or near real time which is impossible in our case.

Hilbert transform also fits for post processing application because when applied at first, for getting real and imaginary part of the signal then followed by the Sagnac frequency estimation, it gives out very precise results and nearly equal to that of AR (2).

However, the generalization that the Autoregressive technique is the efficient than any other is not true because in our current analysis the account is only taken for raw data which does not contains higher frequency contents. The higher frequency contents is mostly associated with the areas where the Earthquake (local seismic) occurs in which the raw data contains frequency which leads to the big variations of the Sagnac frequency.

But in our case most of the data has been taken when there is no higher frequencies or some of them contains data with teleseismic frequencies that are still not as high as that much. In that manner the AR (2) technique is not producing the precise results when the expected frequency range is associated with those from local seismic because there will be large variations of Sagnac frequency.

It would have been possible if there were raw data with large frequency components associated with local seismic activities to clarify the facts that the AR (2) does not yield precise estimation of the Sagnac frequency by processing the data and observe the real results.

But so far, it is only low frequency components that has been used. In most cases when the estimation is done based on the local seismic areas where the frequency contents to be detected is large, FM demodulator is the best technique to be used. This has been pointed out specifically when the GEOsensor was in operation whereby the FM demodulator was used.
Recommendations

Since the main goal of the research was to compare the algorithms aiming at getting the efficient one, there were no comparison that has been done. The main problem arises when the outputs characteristic starts to oscillates. Therefore the recommendations is mainly focuses on the suggested possible cause of the oscillations.

- Since the algorithms might be the cause of the oscillations, a deep analysis of the code that has been used to develop the functions need to be done in the future. This requires deep knowledge of programming and extensive reviews of the frequency estimation techniques to find the fundamental cause of the oscillations and if possible some adjustments are to be done on the code to get rid of the oscillations.

- On the other hand as suggested, the logger might also affect the output characteristics which results to the oscillations, but this is considered to be very minor due to the fact that the logger is to the large extent not related to the data from the ring laser. Since the logger are of different types and for the purpose of not being skeptical it is better in future time to check also if for the other logger the same observations will be seen otherwise the logger will not be considered to be the source of oscillations.
References

7. Alexander Velikoseltsev,’ the development of a sensor model for Large Ring Lasers and their application in seismic studies’.
29. Antonino Daviu, Jose Alfonso ‘Operation of Hilbert-Huang Transform: basic overview and examples’


Appendix A

Source code for the algorithms when estimating Sagnac frequency of a raw data from G-ring laser and C-II ring laser.

%AUTOREGRESSIVE (AR(2)) TECHNIQUE
L=load('rotation.txt'); %First raw data from G-ring laser
fs=10000; %Sampling frequency of the raw data
f=348.5; %Initial estimate of Sagnac frequency
N=10000; %Number of samples in each estimate
[b,a]=butter(2,[0.06969 0.06972],'bandpass');
R_filtered=filter(b,a,L);
tic;
[F,D]=AR2(R_filtered,f,0,N,fs,0); %Output estimated frequency (F) and linewidth (D)
elapsedTime=toc;
for i=1:25
    F(i)=F(i+25);
end
plot(F);
legend('ET=0.48,STD=0.000026'); legend boxoff;
title('AUTOREGRESSIVE AR(2)');
ylabel('frequency (Hz)');
xlabel('Time (sec)');

%QUINN AND FERNANDES TECHNIQUE
L=load('rotation.txt'); %First data from G-ring laser
f=348.5; %Initial estimate of Sagnac frequency
fs=10000; %Sampling frequency for raw data from ring laser
%[b,a]=butter(2,[0.3484 0.3486],'bandpass');
[b,a]=butter(2,[0.06969 0.06972],'bandpass'); %Filtering the raw data for removing noises
R_filtered=filter(b,a,L);
n1=1;
n2=10000;
for i=1:600 %Estimating Sagnac frequency for every sample
tic
    [est(i)] = qnf(R_filtered(n1:n2));
time=toc;
F(i)=est(i)*fs/(2*pi); %Estimated Sagnac frequency
n1=n1+10000;
n2=n2+10000;
end
STD=std(F);
for i=1:41
    F(i)=F(i+41);
end
plot(F);
legend('ET=0.0013, STD=0.0004'); legend boxoff;
title('QUINN & FERNANDES');
ylabel('Frequency(Hz)');
xlabel('Time (Sec)');

%WEIGHTED LINEAR PHASE PREDICTOR TECHNIQUE
L=load('rotation.txt');%First data from G-ring laser
f=348.5;%Initial estimate of Sagnac frequency
fs=10000;%Sampling frequency for raw data
[b,a]=butter(2,[0.06969 0.06972],'bandpass');%Filtering raw data for removing noises
R_filtered=filter(b,a,L);
n1=1;
n2=10000;
for i=1:600%Estimating Sagnac frequency for every sample
tic;
    omegahat(i) = wlp( R_filtered(n1:n2),'kay');
elapsedTime=toc;
    F(i)=omegahat(i)*fs/(2*pi);% Estimated Sagnac frequency
n1=n1+10000;
n2=n2+10000;
end
STD=std(F);
for i=1:41
    F(i)=F(i+41);
end
plot(F);
legend('ET=0.0011, STD=0.00093'); legend boxoff;
title('WEIGHTED LINEAR PHASE PREDICTOR');
ylabel('frequency (Hz)');
xlabel('Time (sec)');
%PISARENKO TECHNIQUE
L=load('rotation.txt'); %First data from G-ring laser
t=348.5; %Initial estimate of Sagnac frequency
fs=10000; %Sampling frequency for raw data
[b,a]=butter(2,[0.06969 0.06972], 'bandpass'); %Filtering raw data for removing noises
R_filtered=filter(b,a,L);
n1=1;
n2=10000;
for i=1:600 %Estimating Sagnac frequency for every sample
tic
[est(i)] = pisarenko(R_filtered(n1:n2));
elapsedTime=toc;
F(i)=est(i)*fs/(2*pi); %Estimated Sagnac frequency
n1=n1+10000;
n2=n2+10000;
end
STD=std(F);
for i=1:41
F(i)=F(i+40);
end
plot(F);
title('PISARENKO');
ylabel('Frequency (Hz)');
xlabel('Time (sec)');
legend('ET=0.00019, STD=0.18'); legend boxoff;

%HILBERT TRANSFORM TECHNIQUE
M = csvread('GRL5.dat',1,0,[1,0,20000000,0]); %Second data from G-ring laser
fs=10000; %sampling frequency
[b,a]=butter(2,[0.3484 0.3486], 'bandpass'); %Filtering raw data
R_filtered=filter(b,a,M);
n1=1;
n2=10000;
%y=hilbert(R_filtered); %analytic signal at once for all input signals
for i=1:600 %Estimating Sagnac frequency for every sample
tic;
x=hilbert(R_filtered(n1:n2)); %analytic signal for each bean
instfreq = (fs*diff(unwrap(angle(x))))/(2*pi); %Estimated Sagnac frequency
ET=toc;
f1=instfreq(length(instfreq));
instf=vertcat(instfreq,f1);
F(i)=mean(instf); % Mean frequency for each sample
n1=n1+10000;
n2=n2+10000;
end
STD=std(F);
F(1)=F(2);
plot(F);
legend('ET=0.0006,STD=0.35'); legend boxoff;
title('HILBERT TRANSFORM');
ylabel('Frequency(Hz)');
xlabel('Time (Sec)');

% AUTOREGRESSIVE (AR(2)) TECHNIQUE
M = csvread('GRL6.dat',1,0,[1,0,20000000,0]); % Second data from G-ring laser
fs=2000; % Sampling frequency
f=348.5; % Initial estimate
N=2000; % Number of samples in each estimate
[b,a]=butter(2,[0.3484 0.3486],'bandpass');
R_filtered=filter(b,a,M);
tic;
[F,D]=AR2(R_filtered,f,0,N,fs,0); % Output estimated frequency (F) and linewidth (D)
elapsedTime=toc;
STD=std(F);
for i=1:25
    F(i)=F(i+25);
end
plot(F);
legend('ET=2.3,STD=0.00003'); legend boxoff;
title('AUTOREGRESSIVE AR(2)');
ylabel('frequency (Hz)');
xlabel('Time (sec)');

% QUINN AND FERNANDES TECHNIQUE
M = csvread('GRL6.dat',1,0,[1,0,20000000,0]); % Second data from G-ring laser
fs=2000; % Sampling frequency
[b,a]=butter(2,[0.3484 0.3486],'bandpass'); % Filtering raw data
R_filtered=filter(b,a,M);
n1=1;
n2=2000;
for i=1:10000
%Estimating Sagnac frequency for every sample
tic
[est(i)] = qnf(R_filtered(n1:n2));
etalyzedTime=toc;
F(i)=est(i)*fs/(2*pi); %Estimated Sagnac frequency
n1=n1+2000;
n2=n2+2000;
end
STD=std(F);
for i=1:25
F(i)=F(i+25);
end
plot(F);
legend('ET=0.0005, STD=0.0004'); legend boxoff;
title('QUINN & FERNANDES');
ylabel('Frequency(Hz)');
xlabel('Time (Sec)');

%WEIGHTED LINEAR PHASE PREDICTOR TECHNIQUE
M = csvread('GRL5.dat',1,0,[1,0,20000000,0]); %Second data from G-ring laser
fs=2000; %sampling frequency
[b,a]=butter(2,[0.3484 0.3486], 'bandpass'); %Filtering raw data
R_filtered=filter(b,a,M);
n1=1;
n2=2000;
for i=1:10000
%Estimating Sagnac frequency for every sample
tic;
omegahat(i) = wlp( R_filtered(n1:n2), 'kay');
etalyzedTime=toc;
F(i)=omegahat(i)*fs/(2*pi); %Estimated Sagnac frequency
n1=n1+2000;
n2=n2+2000;
end
STD=std(F);
for i=1:25
F(i)=F(i+25);
End
plot(F);
legend('ET=0.0005, STD=0.0004'); legend boxoff;
title('WEIGHTED LINEAR PHASE PREDICTOR');
ylabel('Frequency (Hz)');
xlabel('Time (sec)');

%PISARENKO TECHNIQUE
M = csvread('GRL5.dat',1,0,[1,0,20000000,0]); %Second data from G-ring laser
fs=2000; %sampling frequency
[b,a]=butter(2,[0.3484 0.3486],'bandpass'); %Filtering raw data
R_filtered=filter(b,a,M);
n1=1;
n2=2000;
for i=1:10000
    %Estimating Sagnac frequency for every sample
    tic
    [est(i)] = pisarenko(R_filtered(n1:n2));
    elapsedTime=toc;
    F(i)=est(i)*fs/(2*pi); %Estimated Sagnac frequency
    n1=n1+2000;
    n2=n2+2000;
end
STD=std(F);
for i=1:25
    F(i)=F(i+25);
end
plot(F);
title('PISARENKO');
ylabel('Frequency (Hz)');
xlabel('Time (sec)');
legend('ET=0.0005, STD=0.089'); legend boxoff;

%HILBERT TRANSFORM TECHNIQUE
M = csvread('GRL5.dat',1,0,[1,0,20000000,0]); %Second data from G-ring laser
fs=2000; %sampling frequency
[b,a]=butter(2,[0.3484 0.3486],'bandpass'); %Filtering raw data
R_filtered=filter(b,a,M);
n1=1;
n2=2000;
%y=hilbert(R_filtered); %analytic signal at once for all input signals
for i=1:10000
    %Estimating Sagnac frequency for every sample
    tic;
x=hilbert(R_filtered(n1:n2)); %analytic signal for each bean
instfreq = (fs*diff(unwrap(angle(x))))/(2*pi); %Estimated Sagnac frequency
ET=toc;
f1=instfreq(length(instfreq));
instf=vertcat(instfreq,f1);
F(i)=mean(instf); %Mean frequency for each sample
n1=n1+2000;
n2=n2+2000;
end
STD=std(F);
F(1)=F(2);
plot(F);
legend('ET=0.0006,STD=0.35'); legend boxoff;
title('HILBERT TRANSFORM')
ylabel('Frequency(Hz)');
xlabel('Time (Sec)');

% AUTOREGRESSIVE (AR (2)) TECHNIQUE
R1=load('C-II(2).txt'); %Data from C-II ring laser
R2=load('C-II(1).txt'); %Data from C-II ring laser
R=vertcat(R1,R2);
J=R(:,1);
fs=1000; %sampling frequency
f=79.76; %initial estimate of Sagnac frequency
N=1000; %Number of samples in each estimate
[b,a]=butter(2,[0.158 0.16], 'bandpass'); %filter for C-II ring laser
R_filtered=filter(b,a,J);
tic;
[F,D]=AR2(R_filtered,f,0,N,fs,0); %Estimated frequency (F) and linewidth (D)
elapsedTime=toc;
STD=std(F);
F(1801)=F(1800);
for i=1:10
    F(i)=F(i+10);
end
plot(F);
legend('ET=0.59,STD=0.0043'); legend boxoff;
title('AUTOREGRESSIVE AR(2)')
ylabel('frequency (Hz)');
xlabel('Time (sec)');
%QUINN AND FERNANDES TECHNIQUE
R1=load('C-II(2).txt'); %Data from C-II ring laser
R2=load('C-II(1).txt'); %Data from C-II ring laser
R=vertcat(R1,R2);
J=R(:,1);
fs=1000; %sampling frequency
f=79.76; %initial estimate of Sagnac frequency
[b,a]=butter(2,[0.158 0.16], 'bandpass'); %filter for C-II ring laser
R_filtered=filter(b,a,J);
n1=1;
n2=1000;
for i=1:3600 %Estimating Sagnac frequency in each sample
    tic
    [est(i)] = qnf(R_filtered(n1:n2));
    elapsedTime=toc;
    F(i)=est(i)*fs/(2*pi); %Estimated Sagnac frequency
    n1=n1+1000;
    n2=n2+1000;
end
STD=std(F);
F(1801)=F(1800);
for i=1:10
    F(i)=F(i+10);
end
plot(F);
legend('ET=0.0003, STD=0.0045'); legend boxoff;
title('QUINN & FERNANDES');
ylabel('Frequency(Hz)');
xlabel('Time (Sec)');

%WEIGHTED LINEAR PHASE PREDICTOR TECHNIQUE
R1=load('C-II(2).txt'); %Data from C-II ring laser
R2=load('C-II(1).txt'); %Data from C-II ring laser
R=vertcat(R1,R2);
J=R(:,1);
fs=1000; %sampling frequency
f=79.76; %initial estimate of Sagnac frequency
[b,a]=butter(2,[0.158 0.16], 'bandpass'); %filter for C-II ring laser
R_filtered=filter(b,a,J);
n1=1;
n2=1000;
for i=1:3600
    Estimating Sagnac frequency in each sample
    tic;
    omegahat(i) = wlp( R_filtered(n1:n2), 'kay');
    elapsedTime=toc;
    F(i)=omegahat(i)*fs/(2*pi);    %Estimated Sagnac frequency
    n1=n1+1000;
    n2=n2+1000;
end
STD=std(F);
F(1801)=F(1800);
for i=1:10
    F(i)=F(i+10);
end
plot(F);
legend('ET=0.00034,STD=0.0046'); legend boxoff;
title('WEIGHTED LINEAR PHASE PREDICTOR');
ylabel('frequency (Hz)');
xlabel('Time (sec)');

%PISARENKO TECHNIQUE
R1=load('C-II(2).txt');   %Data from C-II ring laser
R2=load('C-II(1).txt');   %Data from C-II ring laser
R=vertcat(R1,R2);
J=R(:,1);
fs=1000;   %Sampling frequency
f=79.76;   %Initial estimate of Sagnac frequency
[b,a]=butter(2,[0.158 0.16], 'bandpass');    %Filter for C-II ring laser
R_filtered=filter(b,a,J);
n1=1;
n2=1000;
for i=1:3600
    Estimating Sagnac frequency in each sample
    tic
    [est(i)] = pisarenko(R_filtered(n1:n2));
    elapsedTime=toc;
    F(i)=est(i)*fs/(2*pi);    %Estimated Sagnac frequency
    n1=n1+1000;
    n2=n2+1000;
end
STD=std(F);
F(1801)=F(1800);
for i=1:10
    F(i)=F(i+10);
end
plot(F);
title('PISARENKO');
ylabel('Frequency (Hz)');
xlabel('Time (sec)');
legend('ET=0.000035, STD=0.01');legend boxoff;

%HILBERT TRANSFORM TECHNIQUE
R1=load('C-II(2).txt');%Data from C-II ring laser
R2=load('C-II(1).txt');%Data from C-II ring laser
R=vertcat(R1,R2);
J=R(:,1);
fs=1000;%Sampling frequency
f=79.76;%Initial estimate of Sagnac frequency
[b,a]=butter(2,[0.158 0.16],'bandpass');%Filter for C-II ring laser
R_filtered=filter(b,a,J);
n1=1;
n2=1000;
for i=1:3600%Estimating Sagnac frequency in each sample
    x=hilbert(R_filtered(n1:n2));%analytic signal for each bean
tic;
    instfreq = (fs*diff(unwrap(angle(x))))/(2*pi);%Estimated Sagnac frequency
    ET=toc;
    f1=instfreq(length(instfreq));
    instf=vertcat(instfreq,f1);
    F(i)=mean(instf);
    n1=n1+1000;
    n2=n2+1000;
end
STD=std(F);
F(1801)=F(1800);
for i=1:10
    F(i)=F(i+10);
end
plot(F);
legend('ET=0.00024, STD=0.06');legend boxoff;
title('Hilbert Transform');
ylabel('Frequency(Hz)');
xlabel('Time (Sec)');