GAARDIAN eLoran Processing Algorithms

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ABSTRACT. GAARDIAN (GNSS Availability, Accuracy, Reliability anD Integrity Assessment for timing and Navigation) is a collaborative project funded by the UK's Department for Business, Innovation and Skills (BIS), Technology Strategy Board (TSB). Lead by Chronos Technology Ltd., GAARDIAN will create a data gathering system, which can be used in the vicinity of mission/safety critical activities to analyse and assess the accuracy and reliability of Positioning, Navigation and Timing (PNT) systems including GPS and eLoran.

The aim is to develop small remote data measurement equipment, or probes, to gather performance data on PNT systems and send the data to a central server for storage, analysis and generation of user alerts. Data compression algorithms are required to take the large amounts of complex data, measured at the probe, and process it into a compressed form. This process conserves data communication bandwidth and storage requirements.

GAARDIAN will open up new markets in safety-critical navigation and timing applications, and will place the UK in a leading position for the future commercial exploitation of a new market for mission-critical PNT integrity monitoring systems. Deployment is expected into PNT markets such as transport and aviation as well as the maritime environment.

Partner organisations include representatives from industry and academia. The GLAs' role, as one of the seven, is to produce the algorithms that will analyse the performance of eLoran at the probes' locations, including, among others, detailed statistics on time of arrival, signal-to-noise ratio, envelope to cycle difference, and local positioning error performance.

In addition to a robust anomaly detection system, the probes will also serve as a vital long-term eLoran monitor system, using GLA sites to gather information about system availability performance, seasonal propagation effects and early skywave statistics. No such long-term and geographically diverse eLoran measurement campaign has thus far been performed in the UK or Europe. This paper presents the technical work so far performed by the GLAs, the results thereof and planned future work.

THE GAARDIAN PROJECT. The GAARDIAN project began as an initiative by the Technology Strategy Board (TSB), part of what is now called the Department for Business, Innovation and Skills (BIS) (previously DIUS). The Technology Strategy Board provides research funding to encourage the development of technology in areas, which are considered vital to the future of the UK economy.

The GLAs, as part of a consortium of seven organisations, led by Chronos Technologies Limited (CTL) submitted GAARDIAN as a proposal to the Technology Strategy Board to address the technology area 'Data Gathering in Complex Environments'. The Technology Strategy Board have awarded £2.2M funding to the project, and work has begun in developing the first GAARDIAN probes.

PARTNER ORGANISATIONS. Each partner in the consortium has their own motivation for participating in the project and contributes their own particular knowledge and expertise.

<u>Chronos Technologies Limited (CTL)</u> – Project lead, CTL has experience providing GPS timing and monitoring equipment to the telecoms industry.

General Lighthouse Authorities (GLA) –Service providers of DGPS and eLoran for maritime navigation users in the UK and Ireland.

National Physical Laboratory (NPL) – Providers of national timing and frequency services.

Imperial College London (ICL) – Centre for Transport Studies, provide radio-navigation expertise.

University of Bath (UoB) – Space weather and GNSS multipath experts.

Ordnance Survey (OS) – Land surveying and mapping, OS operate a network of GPS monitor sites throughout the UK.

British Telecom (BT) – Represent the telecommunications industry, and are users of GPS timing for network synchronization.

OVERVIEW. GAARDIAN is to be a network of data gathering and monitor probes, to be located at the point of service for GNSS and eLoran timing, frequency and navigation users. It is the aim that the probes will provide detailed information on the availability and integrity of GNSS and eLoran signals to the service providers through a web-enabled server interface. Users can access past and current data, and can be provided with alerts in real-time if and when service disruption occurs.

In addition, the probes will be able to gather long-term data, which can be made available through the server for particular users.

A system diagram is shown in Figure 1.

PROBE DESIGN. Each Probe will consist of a GPS receiver, an eLoran receiver, a local timing standard such as a rubidium oscillator and hardware to gather the serial data output by these receivers. A Linux-based PC, also built into the probe, will process this data using custom-written algorithms. Data compression is needed as it is anticipated data bandwidth to the server may be limited at the probe location. Figure 2 shows a block diagram of a probe.

The probe design is based on the existing Synchwatch™ unit, a monitoring and alert system provided by CTL for users of GPS timing [1].

Basing the design on an existing unit speeds up development and implementation but means we have to keep to the processing limit of the Linux engine used by Synchwatch™.

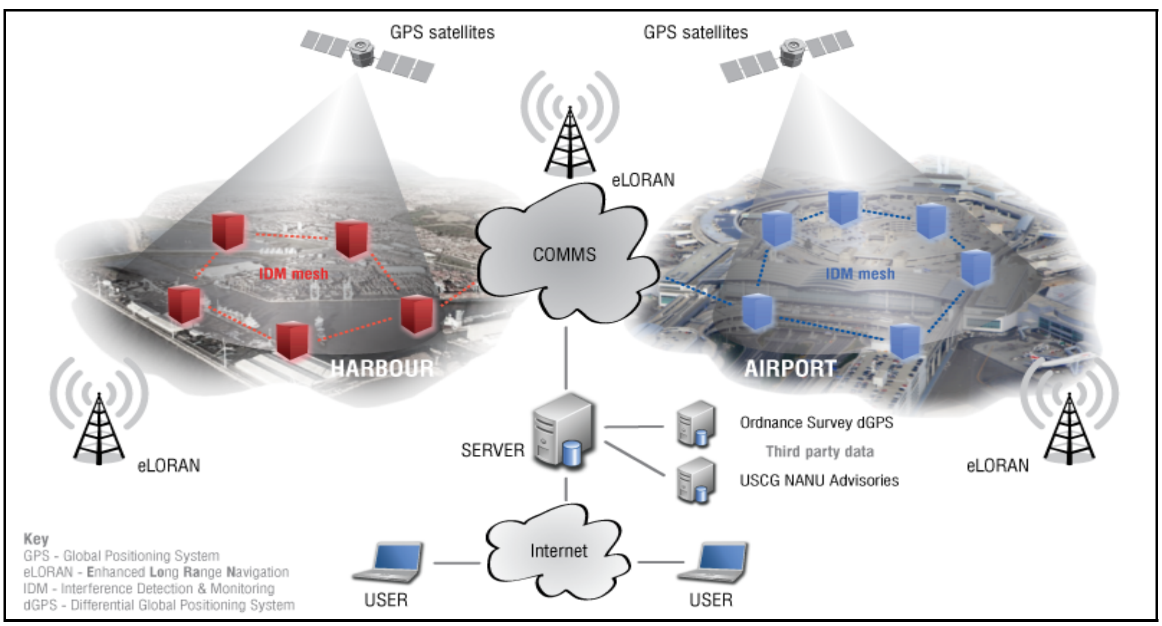

Figure 1 - System Diagram.

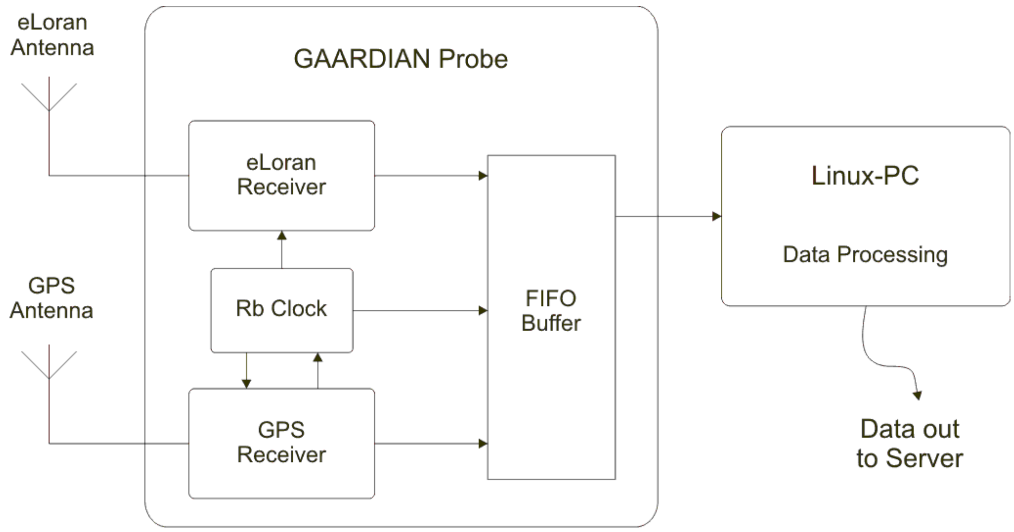

Figure 2 - GAARDIAN probe design.

ALGRITHM DEVELOPMENT. The responsibility for developing each part of the data processing algorithms falls to the consortium member with experience in that particular field. Each processing component is to be submitted to CTL, who possess the coding resources to generate the C++ code, which will run on the final probes.

The GLAs are eLoran service providers for the UK and Ireland, and as such have the responsibility of designing algorithms to assess the eLoran positioning performance.

ELORAN ASSESSMENT. There are a number of minimum performance standards that our eLoran service is required to meet in order to satisfy the safety requirements of the maritime sector. In each case the current or expected future standards are set out, and the methods for assessing whether they have been met are outlined.

ACCURACY. In their assessment of eLoran for Harbour Entrance and Approach [4], the USCG recommended a positioning accuracy figure of between 8-20m (95%). We must ensure that 95% of the positioning fixes obtained by the system are smaller in error than 20m from the true position.

For eLoran we face two problems in achieving this level:

Firstly, we must mitigate the offset in positioning caused by the eLoran Additional Secondary Factors (ASF). Verification of the accuracy of ASF data, however, does not fall under the remit of GAARDIAN.

The second problem concerns the precision or Repeatable Accuracy of the system. ASF data can only remove any absolute offset in the mean eLoran position from ground-truth, a degree of scatter in the positioning will remain. The spread of this scatter is mainly due to the strength of the available signals, local noise and the transmitter geometry. The repeatable accuracy will be measured by GAARDIAN probes in the vicinity of the harbour areas where we provide our differential-Loran service.

AVAILABILITY. The IMO have set a target of 99.8% for electronic position fixing [2]. This means that, on average, the system as a whole should be fit for use 99.8% of the time. This is the equivalent of allowing only one dropped fix, on average, every three-quarters of an hour.

For a number of reasons any individual eLoran station may be flagged as unavailable. A user's receiver requires a minimum Signal-to-Noise-Ratio (SNR) to be able to measure the signal's arrival accurately [3]. In addition, there is a limit to how far the pulse envelope can deviate from the phase of the carrier frequency (Envelope-to-Cycle-Difference, ECD) without harming the measurements.

CCB (Control Centre, Brest) in France performs its own signal quality measurements and can set an individual signal to "blink" if it is found to be out of tolerance, or the signal may be taken off-air completely for maintenance.

By sending the time, duration and cause of each flagged outage back to the server it will be possible to correlate across several probes and differentiate an area-wide transmitter availability problem from a local effect such as noise. In turn we will be able to build up a picture of system availability across the coverage region by location.

INTEGRITY. Integrity is the probability of a user being given Hazardously Misleading Information (HMI); that the receiver will declare a fix to be valid when it is in error. The term “integrity risk” is the probability that a user will experience a position error larger than a threshold value without an alarm being raised within a specified time-to-alarm at any instant of time at any location in the coverage area. The IMO have set an integrity risk target of 10^{-5} [2].

For eLoran GAARDIAN will not be able to verify the integrity checking or RAIM (Receiver Autonomous Integrity Monitoring) of a user’s receiver. RAIM is usually dependent on local noise levels, and RAIM processing algorithms will vary between manufacturers. We may wish to include an independent integrity message as part of our differential-Loran service, and GAARDIAN will be able to verify these messages at some future date.

CONTINUITY. Continuity is defined as the probability that, if the system is working, it will carry on working with integrity for a set length of time. In our case we are assessing eLoran using the new IMO standard of 99.97% over 15 minutes [2], meaning that any 15-minute period chosen at random will have less than a 0.03% chance of containing an outage or integrity breach. This figure is related to Availability through the Mean Time Between Outages (MTBO).

Since MTBO is a statistical measure, its accuracy will depend upon a number of outages observed, so a large amount of data will have to be gathered before reasonable continuity figures can be measured.

ADDITIONAL DATA. We would also like to be able to use GAARDIAN as a data-gathering tool to support our other projects in ASF, eLoran signal propagation and differential-Loran service provision. This means gathering data on the diurnal and seasonal variations in signal characteristics such as ECD, Time of Arrival (TOA) and Signal to Noise Ratio (SNR).

ALGORITHM DETAILS. The following processes have been developed and tested in MatLab™ to measure the four assessment criteria above.

ERROR ELLIPSE. The scatter of Loran position fixes in 24 hours has an elliptical distribution. This distribution is described by the covariance matrix of the position data. The elements of this matrix can be used to derive the parameters of an Error Ellipse. This gives us a good indication of the magnitude of the errors present, and their distribution, or correlation. The ellipse can be described by only 3 parameters.

Figure 3 - The eLoran transmitters used for position fixing in Harwich.

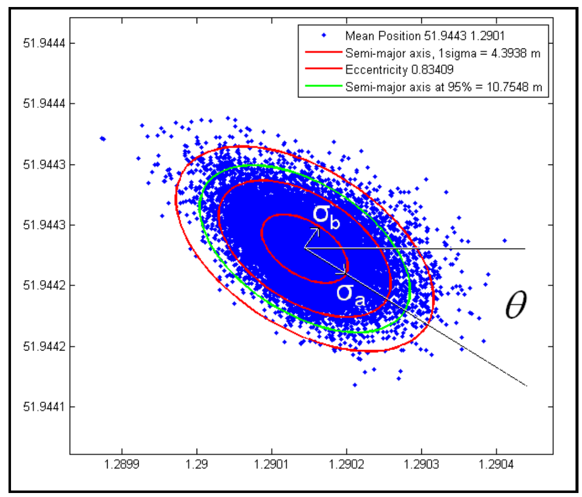

Figure 4 - The positioning Error Ellipse for Harwich, shown in red are 1,2 and 3-sigma ellipses, in green is a 95% ellipse.

In our case, in Harwich, we have a location where the transmitter locations and geometry are good but far from perfect, as shown in Figure 3. Of the five rates (on three transmitters) available here, four are effectively used to give NE/SW precision, only the one rate 6731Y of Anthorn is used to determine the NW/SE precision of positioning. The result is that errors in the direction of Anthorn are greater than the errors in the direction of, say Lessay. This can be seen in Figure 4.

The three parameters shown in Figure 4, σ_a, σ_b and ϑ, can be sent back to the GAARDIAN server to describe the ellipse. Alternatively, the three elements of the covariance matrix can be sent, and the ellipse calculation performed on the server.

The covariance matrix in Latitude and Longitude (x,y) co-ordinates is given by:

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The form of the co-variance matrix in the co-ordinates of the error ellipse (a,b) is:

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C_{ab} is related to C_{xy} by a rotation matrix R:

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The above equation gives the three ellipse parameters related to the observed covariance matrix by three equations:

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Solving these gives σ_a, σ_b and ϑ, in terms of the elements of C_{xy}.

A 95% figure is used to determine accuracy performance, for a bivariate normal distribution. 95% of the position fixes lie within an ellipse with semi-major and semi-minor axes 2.4477 times σ_a and σ_b respectively (the green ellipse in Figure 4). The semi-major axis of this ellipse can be quoted as the 95th percentile accuracy, although this over-bounds the errors and is not consistent with how accuracy is defined.

To use the co-variance matrix to calculate a true circular error which bounds 95% of the position fixes requires the evaluation of a non-analytic elliptic integral. To save processing and coding effort, a simpler measure can be quoted. Often DRMS is used for this purpose:

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Assuming a roughly circular distribution, 95% accuracy is given by 1.7308*DRMS. However, with increasing eccentricity in the ellipse, this relation breaks down, and 1.7308*DRMS under-estimates the 95% errors for highly elliptical distributions.

We choose to use the semi-major axis of the 95% ellipse as our accuracy measure, but with the caveat that this is an over-estimate of the error. DRMS or eccentricity can be checked for comparison.

AVAILABILITY FLAGS. The availability figure for each transmitter is related to the Mean Time Between Outages (MTBO) and the Mean Time to System Restoration (MTSR), both of which are derived from the availability-flag data.

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In Figure 5 below, an ECD-limit flag is demonstrated. In this case three separate instances of ECD-limit breach would be reported, giving a total of 520 seconds without service and a 99.4% availability figure. The data corresponds to a transmitter at a distance of 1100km, at about the edge of its coverage range, so less than perfect availability is expected.

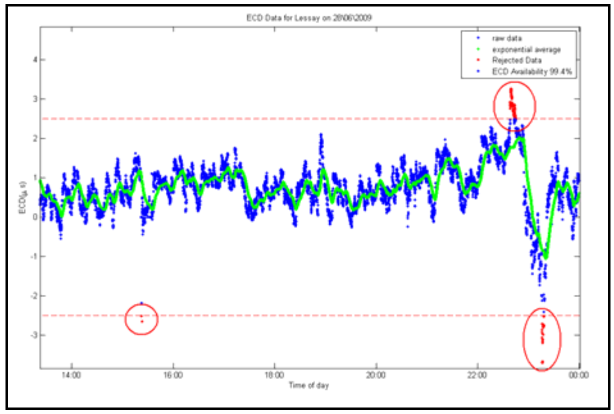

Figure 5 - ECD-Availability of the Lessay signal at a distance of 1100km.

HPL EQUATION. The individual transmitter availability figures have to be related to an overall system availability statistic, a good way to do this is to use a Horizontal Protection Level (HPL) equation.

An HPL works by using an equation to relate the SNR of each signal to an expected error, or variance. A number of such equations have been tested by the GLAs. These variances can be turned into an expected positioning error using the transmitter geometry matrix A:

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Here γ_i is the bearing to the i^{th} Loran transmitter. The expected errors are given in the form of a covariance matrix by the equation:

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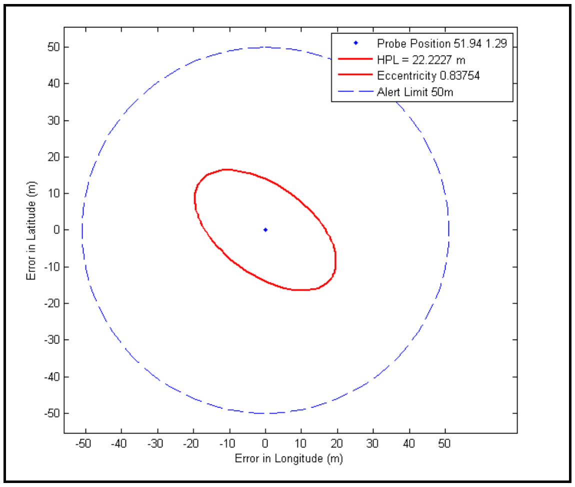

Figure 6 - An HPL Equation for a receiver located in Harwich.

This co-variance matrix can be related to an error ellipse as above, or a simple DRMS figure can be obtained:

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Again, as with accuracy, if this measure exceeds our accuracy limit, we can flag the system as a whole as unusable, and begin counting unusable time to produce a system availability statistic.

CONTINUITY STATISTICS. Continuity is a statistical measure, and is based on the expected length of the next period of un-interrupted service. We can relate the percentage-level (99.97%) and operation time-frame (15 minutes) to a minimum required Mean Time Between Outages (MTBO).

Modelling the availability of the signal as a series of independent events, where at each epoch there is a constant probability of an outage occurring, p, we can derive:

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Where l is the operation time-frame.

Using this we get a minimum MTBO of:

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So the MTBO must be at least 50,000 minutes, or about 35 days. We will monitor MTBO over a long period of time to arrive at a reliable figure.

The continuity of a positioning service must also take into account the probability of losing one or more eLoran signals during the performance of an operation, assuming that sufficient stations were available at the start of the operation. Once we have gathered sufficient availability data, service continuity can be computed for each probe location.

TOA SPECTRAL MODEL. To gather additional data such as TOA we need an efficient model to compress the 17280 data points per transmitter, which are generated each day (assuming one measurement every 5 seconds). A spectral model can efficiently encode the daily variations in TOA with only a few parameters.

The probes will first have to perform a Fast-Fourier-Transform FFT on the data:

$$X_k = \sum_{j=1}^{n} x_j e^{\frac{-2\pi i(j-1)k-1)}{n}}$$

The components X_k are reduced to a few key parameters, the model selects the lowest m spectral components and broadcasts their phase and amplitude for re-construction at the server:

$$y_j = \frac{1}{n}\sum_{k=1}^{m} X_k e^{\frac{2\pi i(j-1)(k-1)}{n}}$$

The model y is represented on the plot shown in Figure 7 by the green line. In this case only 8 spectral components have been used.The mean, the fundamental frequency and the six lowest harmonics. This gives seventeen parameters and a compression ratio of 1000-to-1. The probe ensures reasonable accuracy of the model by checking the residuals:

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If these are found to be too high (for example, more than 10% higher than the TOA-variance), then the number of parameters m can be increased.

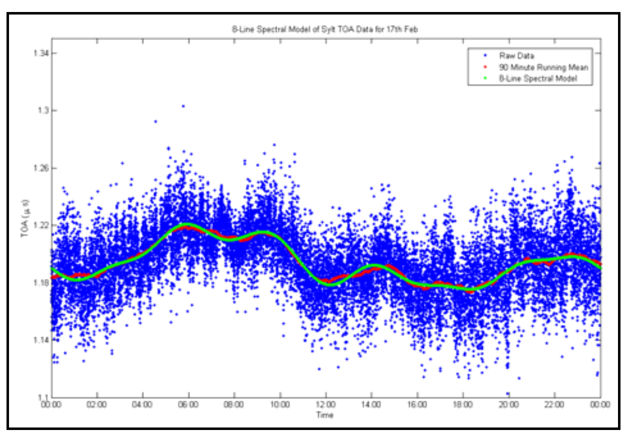

Figure 7 - An 8-line Spectral model of TOA data for Sylt on 17th February 2009.

This model can be used for a number of data sets, such as ECD, SNR or to transmit day/night changes in TOA-variance.

REAL-TIME UPDATES. By holding current estimates of a number of system state parameters on the probe, and updating these on-the-fly as data is measured, GAARDIAN will be able to perform a number of useful tasks.

Users will be able to send a query to the probes and get a real-time response. The probes will be able to provide an accurate and up-to-date picture of the state of the eLoran system. By processing the data in this way, the probes will not have to keep large amounts of data in memory. This technique can be applied to all of the algorithms described. The technique allows more sophisticated outlier rejection methods and it is possible to make the algorithms adaptable and robust against bad data.

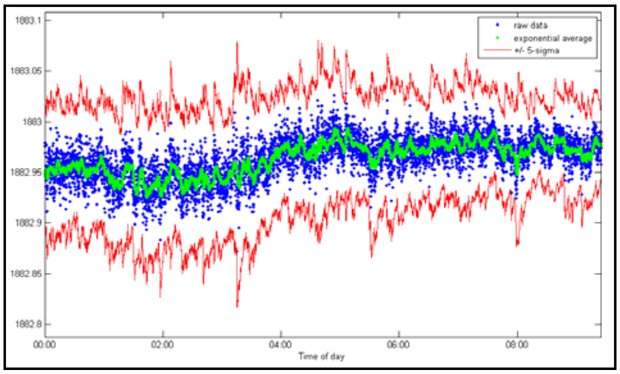

Figure 8 - On-the-fly mean and variance modelling to detect outliers.

Figure 8 shows how the current mean and variance are used to define outlier bounds at +/-5-sigma, the model can reject bad data and coast along using the previous values.

To calculate the on-the-fly mean we use:

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Similarly, the on-the-fly variance can be computed by:

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The exponential smoothing technique applies a low-pass filter to the data, and the parameter α must be chosen depending on the amount of smoothing which is needed. We can relate alpha to the time-constant of a low-pass filter as below:

$$\tau = \frac{(1-\alpha)T_s}{\alpha}$$

Where T_s is the eLoran measurement epoch, or sampling period, given in seconds. In Figure 8 we have used a value $\alpha = 0.05$, which is equivalent to a low-pass filter with $\tau = 95$ seconds.

ALGORITHM IMPLEMENTATION. Several of the algorithms are able to self-start when run on the probe; that is, by measuring the noisiness of the data the parameters of the model can adapt to the environment. In some cases, such as choosing appropriate levels of exponential smoothing, or testing the degree of outlier-rejection it is necessary to run real data through the models and make manual adjustments.

The Harwich prototype differential-Loran Reference Station contains very similar hardware to the GAARDIAN probe, including eLoran and GPS receivers, a Rb oscillator and a PC platform. The PC runs Windows and so we are able to implement our algorithms in MatLab™ without having to be concerned with processing power or memory capacity.

MATLAB IMPLEMENTATION. Figure 9 shows a screen-shot of our MatLab™ implementation. Initially this ran on a separate laptop PC and used past data log files created by the Reference Station. It has been further developed and is capable of being run live on the dLoran station itself.

FUTURE WORK. The work is far from complete. We will need to finalise the development of the GLAs' eLoran algorithms, and test and validate them using the Reference Station implementation.

The delivery of algorithms for a GAARDIAN prototype probe is expected by the end of November.

This first fully functional prototype GAARDIAN probe is expected to be very similar to our dLoran Reference Station implementation, the algorithms will be run on a powerful PC under the MatLab™ environment. A later effort by the CTL team will port this code to C++ to be run on a Linux-based plaform for use within the probe.

As soon as the probes have been developed we expect deployment and data gathering to begin.

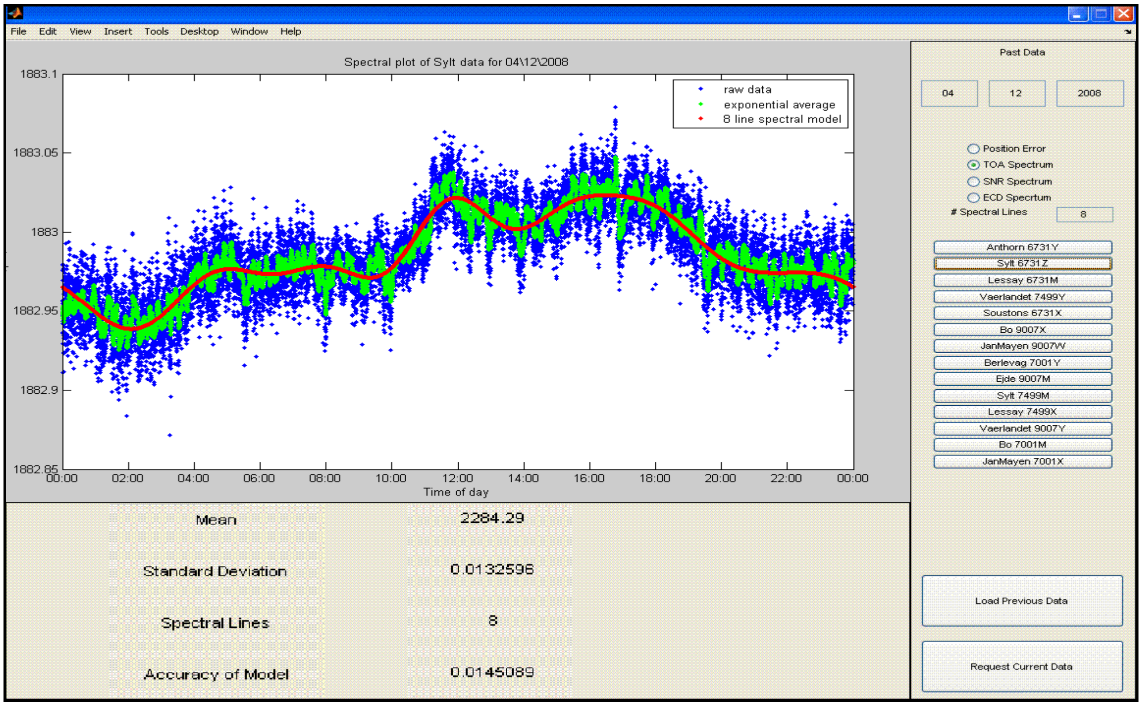

Figure 9 - GAARDIAN algorithm implementation in MatLab

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