eLoran Processing Algorithm Development for GAARDIAN Remote Probes

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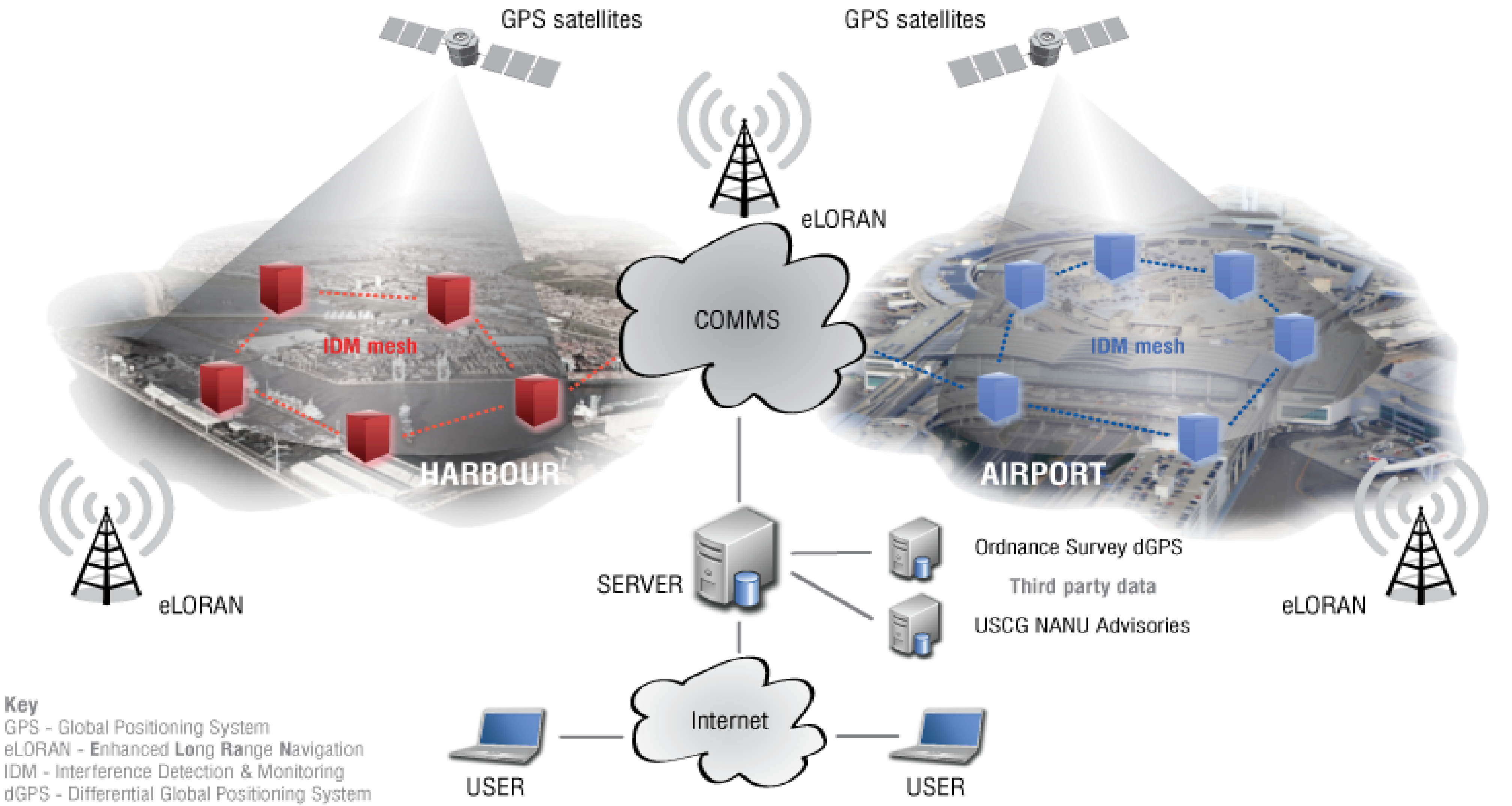
History of GAARDIAN

- Nov 2007: Technology Strategy Board initiative
  - Part of the Department for Innovation, Universities and Skills (DIUS)
  - Promotes innovation in technology by investing in research
  - “Data Gathering in Complex Environments”
- Chronos Technology Limited (CTL) lead
  - Consortium of seven partners
- April 2008: GAARDIAN proposal submitted to TSB.
- June 2008: £2M awarded to the project

Overview of GAARDIAN

-GNSS Availability Accuracy Reliability anD Integrity Assessment for timing and Navigation



Why are the GLA Involved?

- CTL Syncwatch™ for timing applications
  - Monitors GPS at the point of service
  - Our service provision is in the positioning domain
- Where we want GAARDIAN:
  - Harbour areas
  - Lighthouses
  - dLoran reference stations
- What we want GAARDIAN to do:
  - Assessment of GLA transmitter at Anthorn
  - Current eLoran system information
  - dLoran correction integrity check
  - Archive past data
- How…

GLA Algorithms:

- Navigation parameters
  - Accuracy
  - Availability
  - Integrity
  - Continuity
- Also…
  - Signal TOA data
- Data compression
  - 17280 data points per variable, per transmitter, per day
  - No loss of information

Accuracy

- Target of 8-20m (95%) for Harbour Entrance and Approach
  - Depends on providing ASF data and dLoran corrections.
- Repeatable Accuracy (precision) indicates where 20m can be met
  - Depends on available signals
  - Transmitter geometry
- Error Ellipses to represent accuracy
  - Give an indication of expected errors (95%)
  - Representative of transmitter geometry
  - Can be described by 3 parameters only

Error Ellipse

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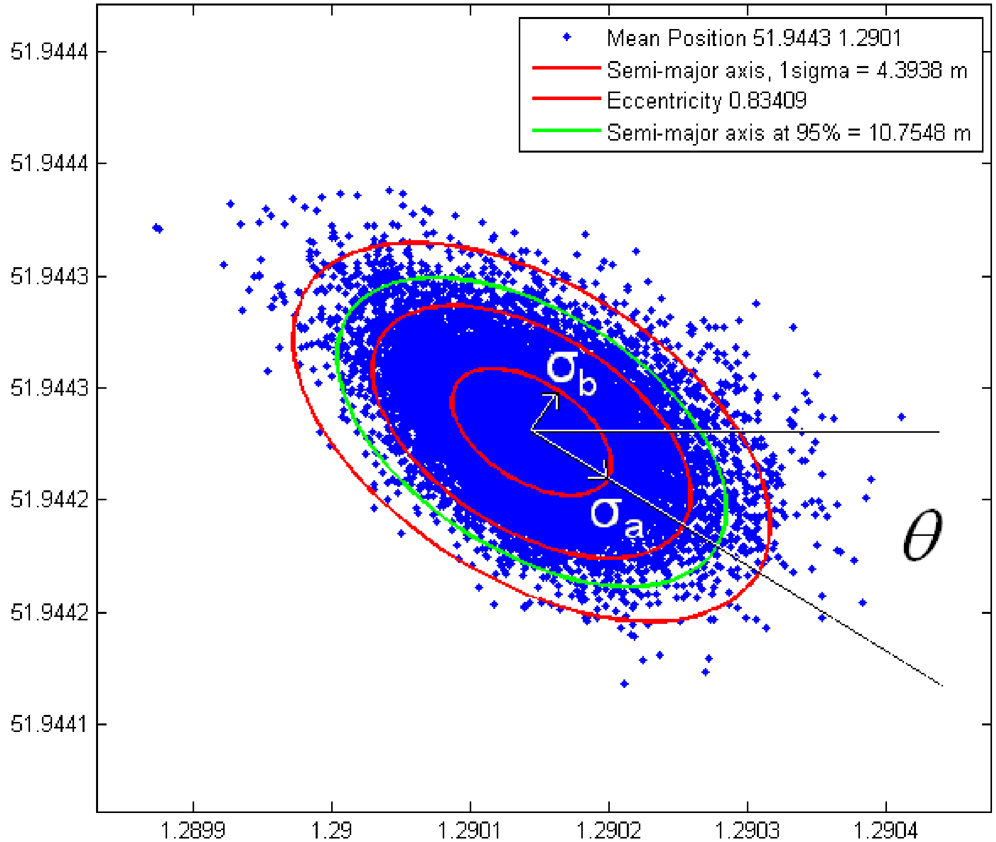

- Ellipse Parameters:

$$C_{ab} = \begin{pmatrix} \sigma_a^2 & 0 \\ 0 & \sigma_b^2 \end{pmatrix} \qquad R = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}$$

- Co-Variance Matrix:

$$C_{xy} = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{pmatrix}$$

- Related by:

$$C_{ab} = R \cdot C_{xy} \cdot R^T$$

Covariance Calculation

- Covariance can be found without storing all the day’s data
- Real-time updates to mean and variance:

$$\mu_{n+1} = K \cdot x_{n+1} + (1 - K) \cdot \mu_n$$

$$\sigma_{n+1}^2 = (1 - K) \cdot \left\{ K \cdot (x_{n+1} - \mu_{n+1})^2 + \cdot \sigma_n^2 \right\}$$

- Or, as a covariance matrix:

$$C_{n+1} = (1 - K) \cdot \left\{ K \cdot \left(\underline{x}_{n+1} - \underline{\mu}_{n+1} \right)^T \times \left(\underline{x}_{n+1} - \underline{\mu}_{n+1} \right) + C_n \right\}$$

- Where

$$K = \frac{1}{n+1}$$

Availability

- System availability target of 99.8%, (99.95% per transmitter)
- Signal availability flags:
  - SNR limits
  - ECD limits
  - Blink and cycle-selection warnings
  - Signal off-air
- System availability:
  - HPL breaches Alert Level
  - System availability statistics calculated

SNR and ECD limits

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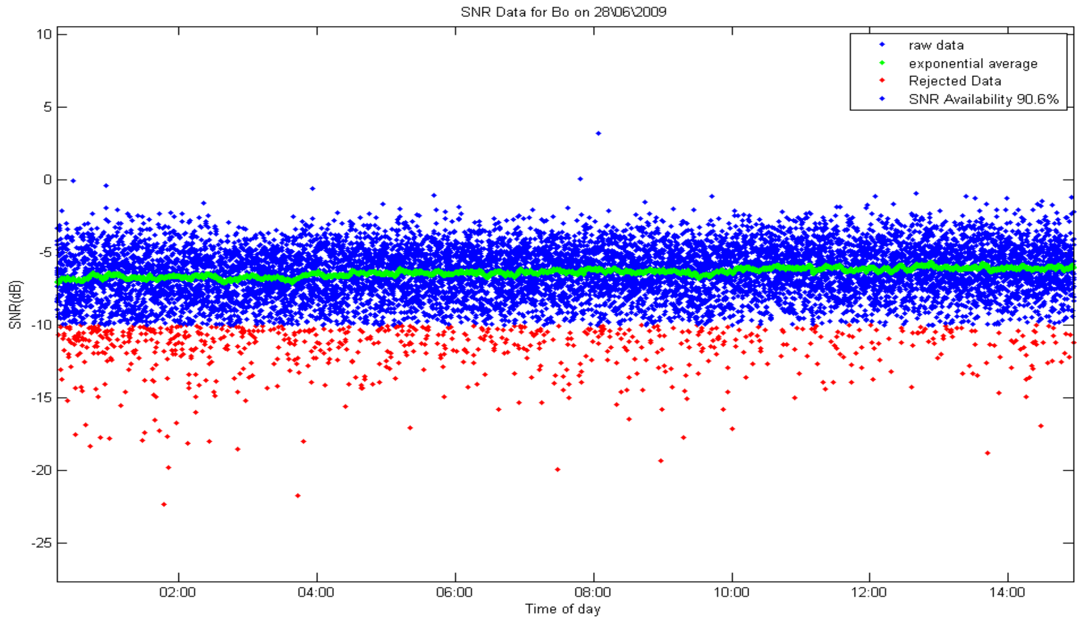
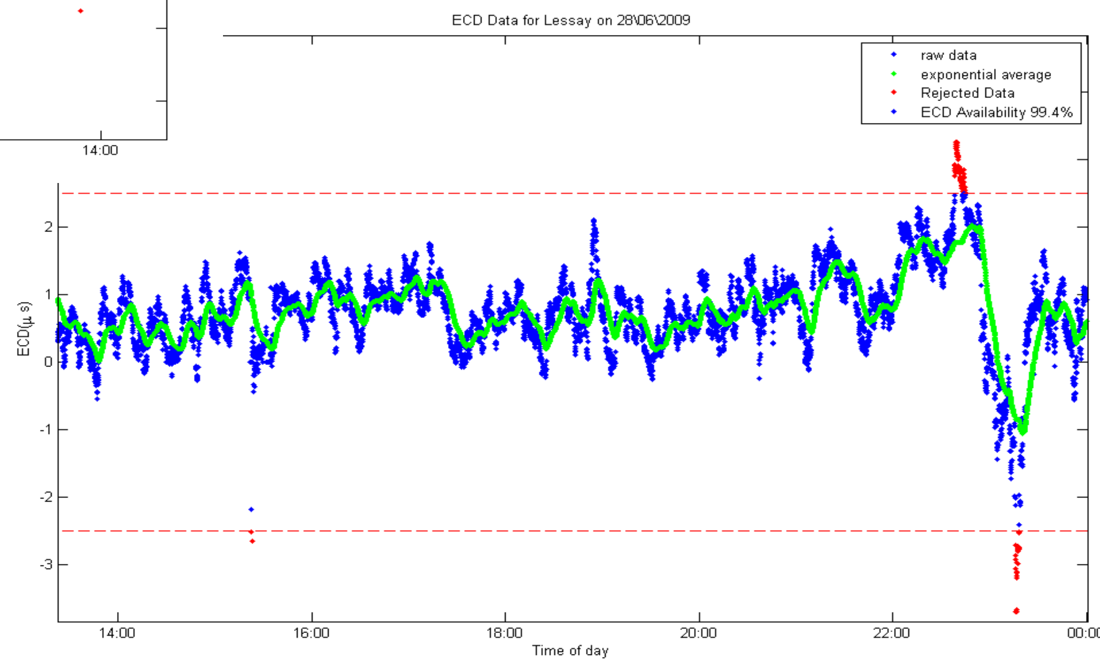


- SNR should be above -10dB for all usable signals.
- Any data below this must be rejected as unusable.



- Any ECD above or below 2.5 micro-seconds is unusable.
- A chance of wrong-cycle selection occurs beyond these bounds

HPL error bounds

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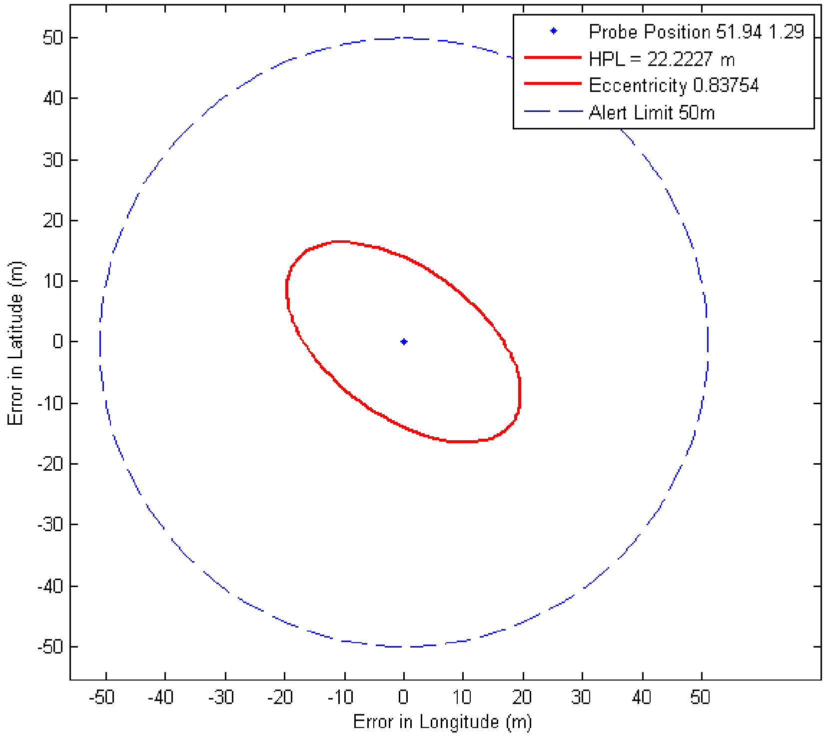


- TOA-variances based on SNR
- Weighting matrix (W)

$$W = \begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \sigma_n^2 \end{pmatrix}^{-1}$$

- Using the Design Matrix (A) of transmitter bearings (g):

$$A = \begin{pmatrix} \sin(\gamma_1) & \cos(\gamma_1) \\ \vdots & \vdots \\ \sin(\gamma_n) & \cos(\gamma_n) \end{pmatrix}$$

$$C_{xy} = \left(A^T \cdot W \cdot A\right)^{-1}$$

Integrity

- A measure of the trustworthiness of the system
  - Expressed as the probability of HMI
  - Target 10^{-5} (equivalent to one fix in 15 hours)
- GAARDIAN is not intended as an Integrity Monitor for eLoran
  - Depends on local radio noise environment
  - Position validation / RAIM is the job of a user's receiver
- Integrity messages to be carried by the Loran Data Channel
  - Generated by dLoran system
  - Will only apply to users of maritime dLoran

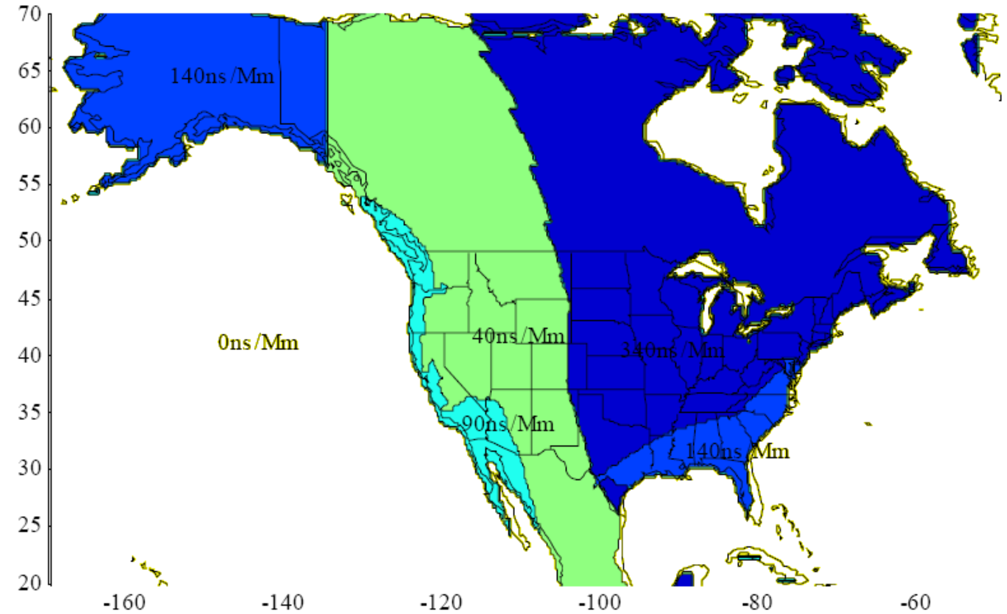
Continuity

- The probability that, if the system is available, it will continue to be available for a period of time
- Our target is 99.97% over 15 minutes
- GAARDIAN will generate continuity parameters based on
  - System availability
  - Mean Time Between Outages (MTBO)
- Parameters will improve in accuracy the longer the probes are in operation.

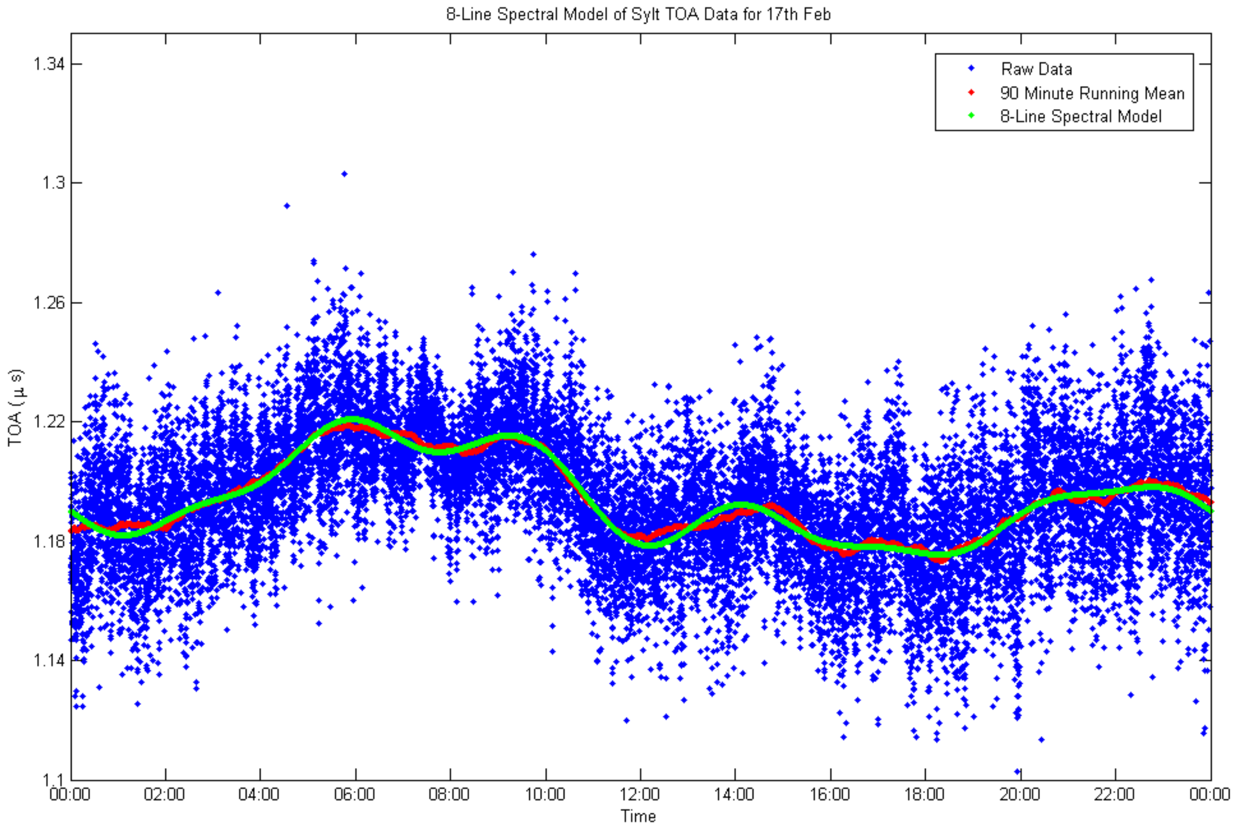
Additional Data: Time Of Arrival (TOA) Variation

- Providing dLoran required knowledge of ASF- variations
- Was done in the US by the USCG (Figure)
- Has not been done in Europe
- The data will be needed for dLoran projects
- Measure TOA variations
  - Diurnal
  - Seasonal
  - Spatial correlation

Figure 4.4-1. Temporal Variation Regions for the United States



Spectral Model



- Spectral components of data:

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

- Reconstructing m spectral lines:

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

- Model accuracy is given by the residuals:

$$\sigma^2 = \frac{1}{n} \sum_{j=1}^{n} (x_j - y_j)^2$$

Real-time GAARDIAN

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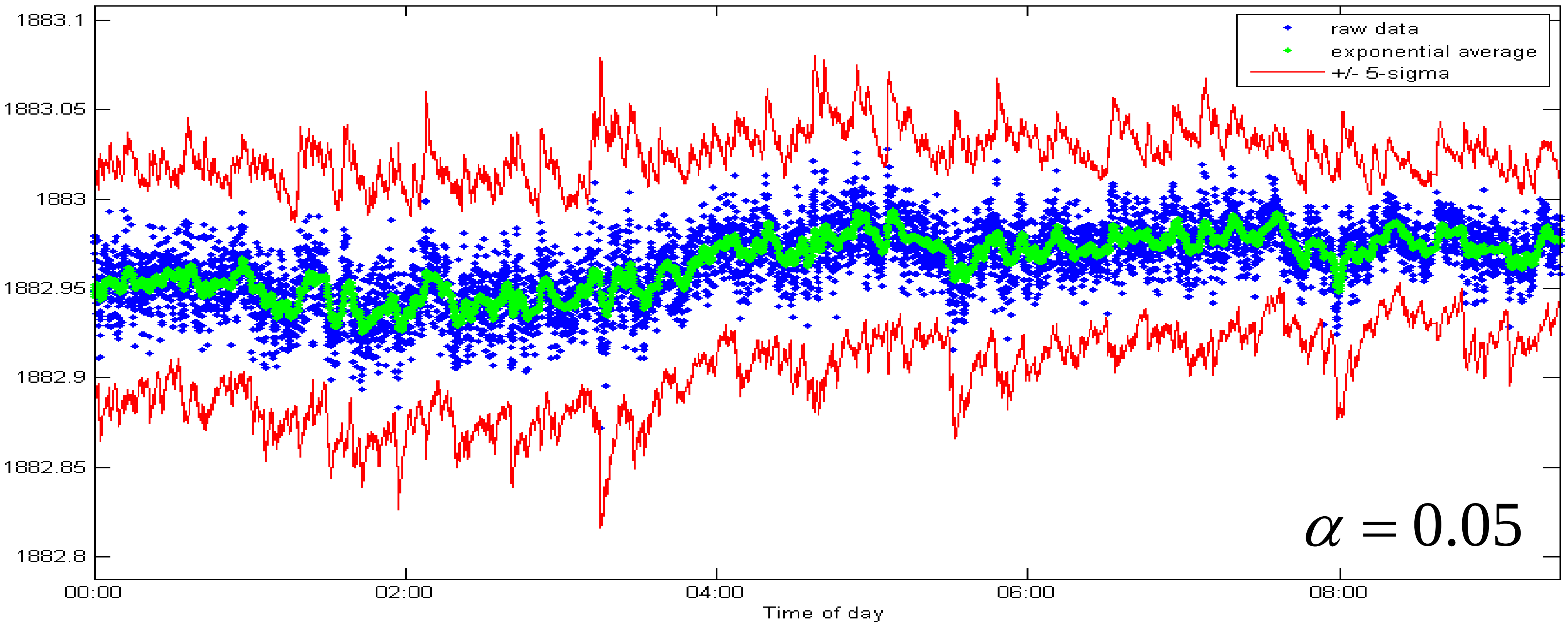
- All well and good as a passive monitoring network
- GAARDIAN server to provide real-time alerts:
  - Interruption of eLoran signals
  - Interference / Jamming events
  - Integrity risks
- Current view from the probes
  - Can query probes from the server
  - Get instant feedback on the state of eLoran at a location
  - Download data from the probes on request.
- Use exponential averaging…

Real-Time Updates

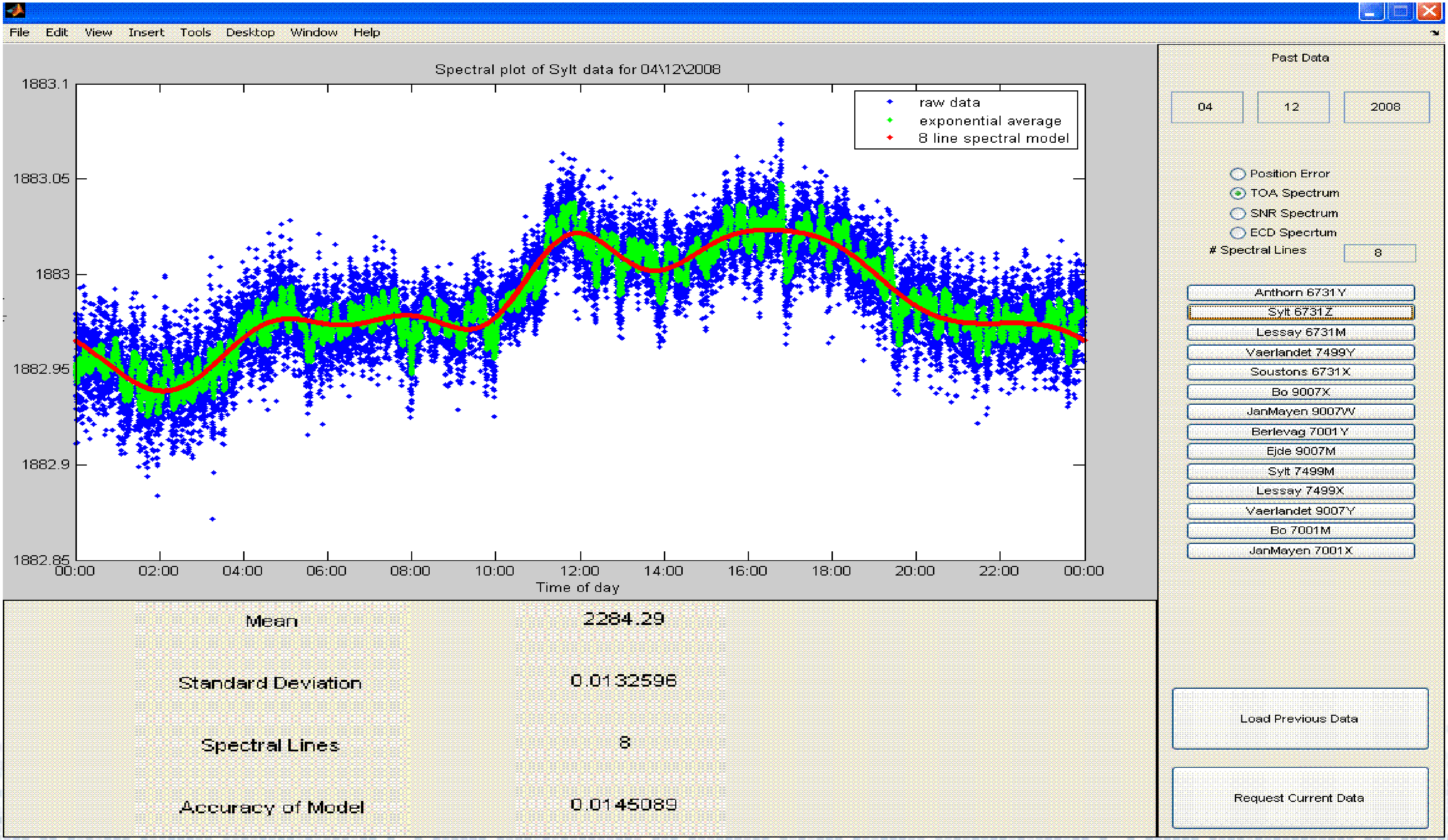
- Mean: $$\mu_n = \alpha \cdot x_n + (1-\alpha) \cdot \mu_{n-1}$$
- Variance: $$\sigma_n^2 = \alpha \cdot (x_n - \mu_n)^2 + (1-\alpha) \cdot \sigma_{n-1}^2$$



GLA Algorithm Implementation

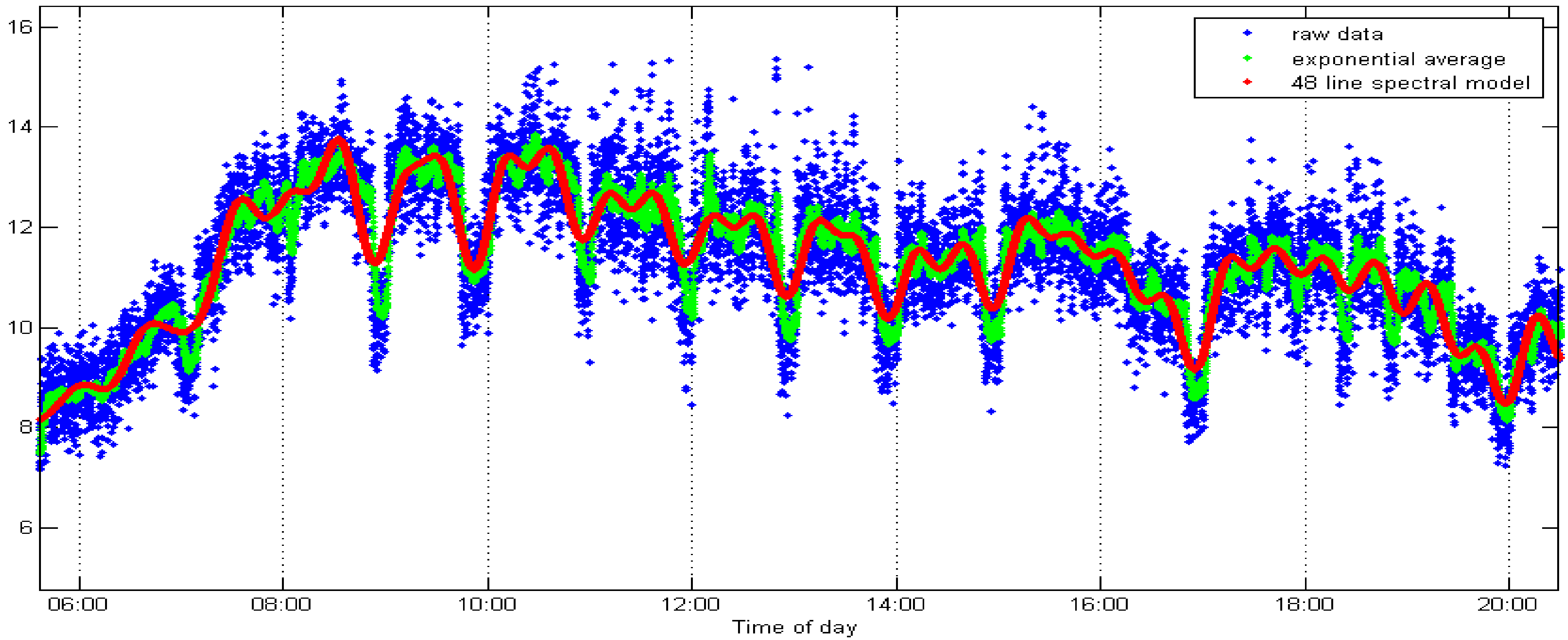
- Our dLoran Station is similar to a GAARDIAN Probe
- We can implement the algorithms to assess their function
- dLoran Station will now be able to produce:
  - Daily spectral plot
  - Real-time parameter updates
  - Error ellipse parameters
  - Alert flags
  - Availability counters

GLA Algorithm Implementation



Case Study: Local SNR Effect

- Periodic lows in SNR were observed
- 24 and 48-line spectral models showed a clear drop in SNR of 2-3 dB every hour



Case Study: Local SNR Cause

Case Study: Local SNR Cause

Correlation with train timetable:

Wed 2 Sep 2009

Outward Journey

prev day next day

Services (Showing all 22 services)

Depart	Arrive	Changes	Duration	Notes
05:51	06:14	0	0:23hrs	
06:36	06:57	0	0:21hrs	
07:35	07:56	0	0:21hrs	
08:29	08:55	0	0:26hrs	
09:22	09:44	0	0:22hrs	
10:29	10:56	0	0:27hrs	
11:26	11:53	0	0:27hrs	
12:26	12:53	0	0:27hrs	
13:26	13:53	0	0:27hrs	
14:26	14:53	0	0:27hrs	
15:26	15:53	0	0:27hrs	
16:26	16:53	0	0:27hrs	
17:21	17:47	0	0:26hrs	
17:55	18:19	0	0:24hrs	
18:23	18:46	0	0:23hrs	

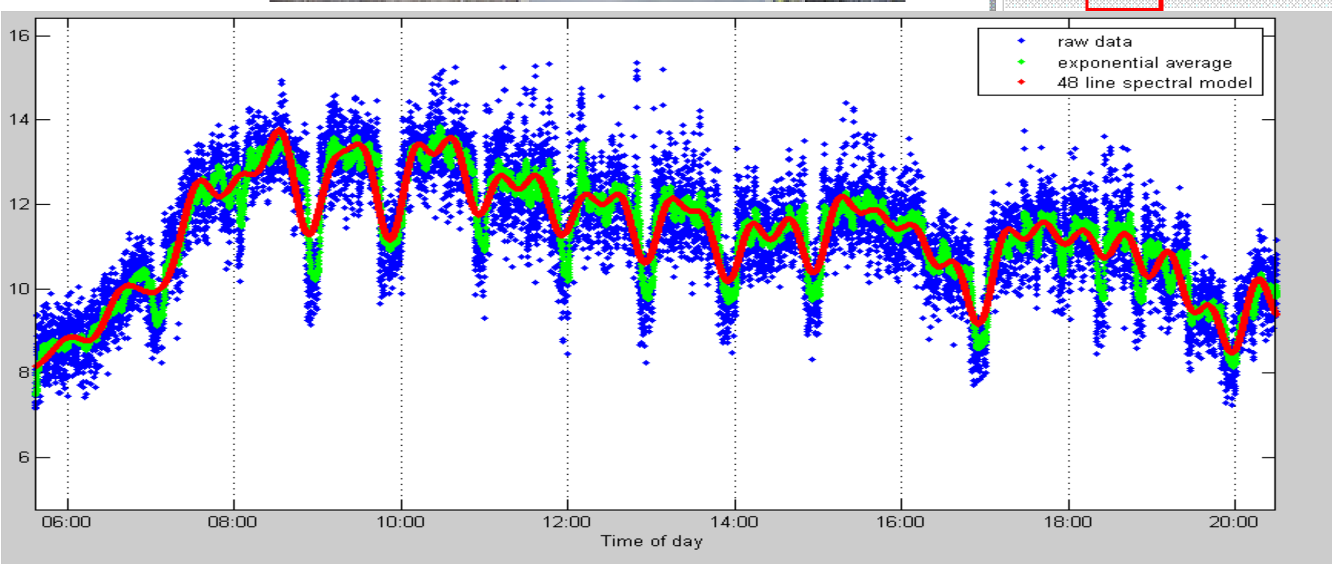
Wed 2 Sep 2009

Return Journey

prev day next day

Services (Showing all 22 services)

Depart	Arrive	Changes	Duration	Notes
05:37	05:58	0	0:21hrs	
06:22	06:42	0	0:20hrs	
07:08	07:29	0	0:21hrs	
08:00	08:21	0	0:21hrs	
09:00	09:21	0	0:21hrs	
10:00	10:21	0	0:21hrs	
11:00	11:21	0	0:21hrs	
12:00	12:21	0	0:21hrs	
13:00	13:21	0	0:21hrs	
14:00	14:21	0	0:21hrs	
15:00	15:21	0	0:21hrs	
16:05	16:26	0	0:21hrs	
17:00	17:21	0	0:21hrs	
17:53	18:14	0	0:21hrs	
18:25	18:46	0	0:21hrs	
18:53	19:14	0	0:21hrs	
19:28	19:49	0	0:21hrs	
20:00	20:21	0	0:21hrs	
20:33	20:55	0	0:22hrs	
21:00	21:21	0	0:21hrs	
21:54	22:15	0	0:21hrs	
23:05	23:26	0	0:21hrs	



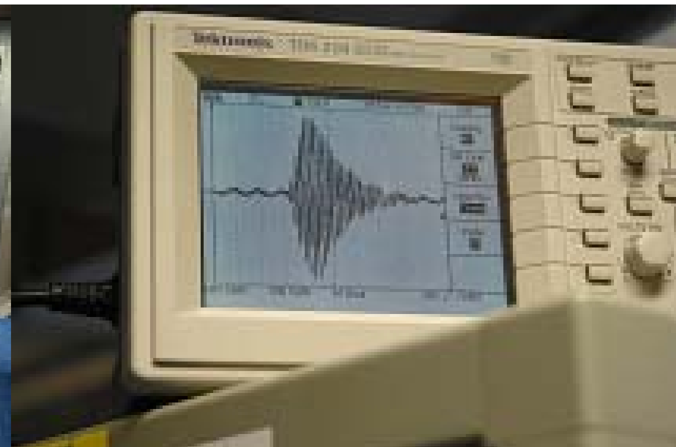
Conclusion

- Algorithms have been designed to monitor eLoran
  - Accuracy
  - Availability
  - Integrity
  - Continuity
- Additional eLoran TOA data-gathering
- Adaptive modelling of data, and on-the-fly system state updates
- Test-bed implementation on dLoran station
- The trains are running on time!

Future Work

- Algorithm Implementation and Testing:
  - Algorithm operation
  - Adaptability and stability
  - Additional Algorithms to implement
- Work with other partners to create first GAARDIAN prototype
- GAARDIAN to become a commercial reality by the end of 2011
- Future projects to include GAARDIAN data
  - European eLoran propagation study
  - Future differential-Loran projects
  - More study of eLoran…

Thank you!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