# LDaC: A Wideband Loran Data Acquisition System

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## Abstract

Loran-C provides timing and positioning services which are suitable for GPS backup in the National Airspace System (NAS). To assess the system's ability to provide the necessary accuracy, integrity, availability and continuity, a variety of analyses and measurement tasks are underway. These tests have produced airframe calibration and flight data files which are a portion of the information required to characterize in-flight airframe charging-discharging noise effects on Loran-C availability. Within the ongoing FAA evaluation program, the Loran Integrity and Accuracy Performance Panels identified the need for a rapid-response recording/analysis/distribution for Loran-C data, as various what-if questions are addressed. Specifically, efforts are currently being made to collect data in order to better characterize the noise in the Loran band. We anticipate that the future Loran-C program, in addition to the ongoing evaluation of Loran-C performance in the National Airspace System (NAS), will certainly include the development of an approval/certification path for proponent avionics. As a part of the knowledge base for this development, access to full-spectrum Loran-C + noise is required. We need to record and analyze wideband Loran-C signals, produce reports and databases, and make the results available to the project team for development of such documents as RTCA MOPS / MASPS and FAA Orders / Standards / Advisory Circulars. An FAA-resident "TSO Database" is another product which can be supported.

Alion Science & Technology (Alion), in support of the U.S. Coast Guard Academy (USCGA), has produced a digital down converter (DDC) based Loran receiver. Development of this receiver was started by the Coast Guard Academy in 1997 for DARPA. Starting in 2001, the FAA sponsored further development of the receiver to support operation in aircraft and using H-field antennas. In recent years, Alion has made improvements to the receiver to enable operation as an Additional Secondary Factor (ASF) measurement tool. This paper discusses the development of a new Loran data acquisition system called LDaC (**L**oran **Da**ta **C**apture) that meets the design goals of wide bandwidth, multi-channel, low cost, and open data format with the system design freely available to the Loran community. The COTS hardware and Alion-developed software are described as well as system design choices.

## Introduction

Loran-C provides timing and positioning services which are suitable for GPS backup in the National Airspace System (NAS). The Loran-C system is currently approved for air navigation use in enroute and terminal-area phases of flight. The FAA has an ongoing program to evaluate Loran-C as an augmentation to GPS and other navigational aids for use in the NAS. Suitability for flight operations including enroute and terminal area navigation plus instrument approach guidance are to be evaluated through analysis and demonstration. Required Navigation Performance at the 0.3 level is the expectation.

To assess the system's ability to provide the necessary accuracy, integrity, availability and continuity, a variety of analyses and measurement tasks are underway. During 2003-4, a series of ground and flight evaluations were carried out by the FAA's W. J. Hughes Technical Center (WJHTC). These tests have produced airframe calibration and flight data files which are a portion of the information required to characterize in-flight airframe charging-discharging noise effects on Loran-C availability.

These data were used for initial analyses, the results of which were included in the FAA report on Loran-C to U.S. DOT on March 31, 2004[1].

Within the ongoing FAA evaluation program, the Loran Integrity and Accuracy Performance Panels identified the need for a rapid-response recording/analysis/distribution for Loran-C data, as various what-if questions are addressed. Specifically, efforts are currently being made to collect data in order to better characterize the noise in the Loran band. We anticipate that the future Loran-C program, addition to the ongoing evaluation of Loran-C performance in the National Airspace System (NAS), will certainly include the development of an approval/certification path for proponent avionics. As a part of the knowledge base for this development, access to full-spectrum Loran-C + noise is required. We need to record and analyze wideband Loran-C signals, produce reports and databases, and make the results available to the project team for development of such documents as RTCA MOPS / MASPS and FAA Orders / Standards / Advisory Circulars. An FAA-resident "TSO Database" is another product which can be supported. The data products can also be made freely available to equipment manufacturers for design and testing activity.

Alion Science & Technology (Alion), in support of the U.S. Coast Guard Academy (USCGA), has produced a digital down converter (DDC) based Loran receiver [2]. Development of this receiver was started by the Coast Guard Academy in 1997 for DARPA. Starting in 2001, the FAA sponsored further development of the receiver to support operation in aircraft and using H-field antennas [3, 4]. Alion personnel have been involved with the development of this receiver since the beginning. In recent years, Alion has made improvements to the receiver to enable operation as an Additional Secondary Factor (ASF) measurement tool. Under subcontract to AMA, working for the WJHTC under Cooperative Agreement 04-G-0057, we have developed a digitizing and recording instrument which is based on past USCG/Alion developments. The goal was to design and build a wideband data acquisition system for Loran with the following criteria:

- >30kHz bandwidth
- Multi-channel
- Low cost
- Open data format
- System design freely available to Loran community

This paper documents the design and use of the instrument. It is expected to find uses in both laboratory and flight settings in the future as the Loran-C program continues.

# Hardware Components

The LDaC (**L**oran **Da**ta **C**apture) system hardware consists of the following components:

- computer with at least 1 PCI slot
- Adlink PCI-9812 A/D board
- Krohn-Hite analog RF front end
- E and/or H-field antennas

The system is connected as shown in Figure 1. Individual components are discussed in the following sections.

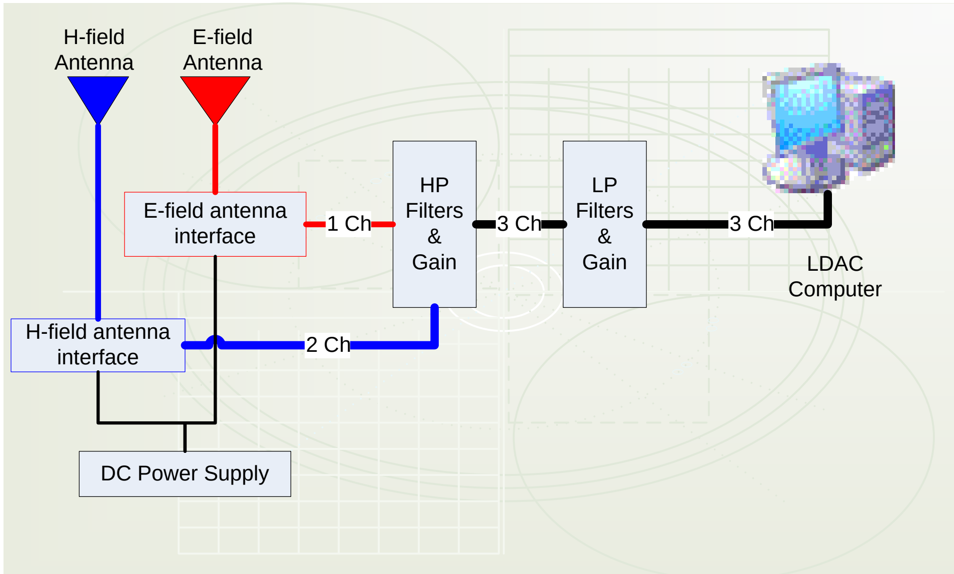


**Figure 1: LDAC System Block Diagram.**

### Antennas and Antenna Interfaces

Any antenna designed for the 100 kHz band could be used with the system. As assembled, the system uses one Megapulse E-field antenna and one Megapulse H-field antenna (Figure 2).

**Figure 2: Megapulse E-field antenna (left) and H-field antenna (right).**

Each antenna is supplied with an antenna cable that connects to the antenna interface. Each antenna interface (Figure 3) runs on DC power and provides initial amplification and filtering.


**Figure 3: H-field (left) and E-field (right) antenna interfaces..**

## RF Front End

The connections between the antenna interfaces and the filter stages are made with coaxial cables with BNC connectors. Bandpass filtering and amplification in the range of 50-150 kHz is provided using the Krohn-Hite filter components. Two options are provided: fixed gain, inline filter modules (models FMB300 single channel and FMB3023 dual channel, shown in Figure 4) and a programmable gain unit (Model 3384, Figure 5). The delivered version uses the modules configured as highpass filters with a cutoff of 50 kHz and a gain factor of x4. The programmable unit is set for lowpass filtering with a cutoff of 150 kHz and the gain adjusted as needed.


**Figure 4: Krohn-Hite Inline Filter Modules.**


**Figure 5: Krohn-Hite Programmable Filter Model 3384.**

## Computer with A/D Board

The connections from the output of the filter to the LDaC computer (Figure 6) are also made using coaxial cables with BNC connectors. The three channels are connected to channels 1, 2, and 3 on the Adlink PCI-9812 A/D board (Figure 7). Any modern computer will do as long as it has a PCI slot for the Adlink board and sufficient disk storage space for the data that will be collected. To eliminate possible interferences with the data collections things like screen savers and software updates should be turned off.


**Figure 6: LDaC Computer Unit.**


**Figure 7: Adlink PCI-9812 board showing antenna and clock connections.**

# System Design

It was desired to make the LDaC system capture a wide bandwidth; 100 kHz was chosen as being sufficiently large given that the typical Loran band of interest is only 30 kHz. With a center frequency of 100 kHz this gives a band of interest of 50-150 kHz.

The sampling frequency was desired to be as low as possible to minimize the amounts of data being handled but high enough to reduce the required performance of the analog filters. The analog front-ends readily available as commercial off-the-shelf (COTS) items typically have $8^{th}$ order analog filters. An analysis was done of what would be a sufficient sampling frequency using this as a limit. This is shown in Figure 8. The $8^{th}$ order filter response in dB vs. frequency in kHz is shown by the blue line. The frequency band of interest (50-150 kHz) is shown by the yellow box. It was also desired to keep the sampling frequency an even fraction of 10 MHz so that a standard 10 MHz reference could be used for the A/D board clock. A 1 MHz sampling frequency ($F_S$) was chosen to meet these parameters. With $F_S$ = 1 MHz, the folding frequency is 500 kHz. Since 500 kHz is 350 kHz away from the upper limit of the frequency band of interest (150 kHz), the frequencies that will be folded into the band of interest will start at 500 + 350 = 850 kHz (this is shown by the red arrows). At 850-950 kHz the 8$^{th}$ order analog filters provide >120dB of protection which should be more than sufficient.

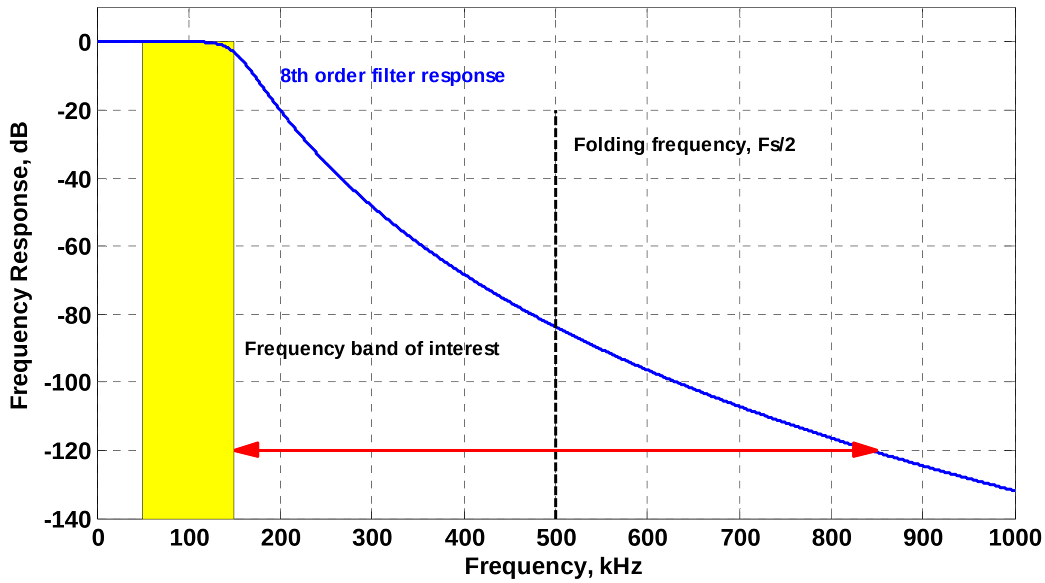


**Figure 8: 8th Order Filter Response.**

After the data is sampled at 1 MHz it is down-converted to baseband using I&Q demodulation. In I&Q demodulation, the passband signal (for Loran, centered at a carrier frequency ($f_c$) of 100 kHz) is split into two signals, one multiplied by a cosine at the carrier frequency and one multiplied by a sine at the carrier frequency (see Figure 9). Low-pass filtering each signal removes the double frequency components and leaves just the baseband in-phase (I) and quadrature (Q) signals. These signals are then be decimated (in this case by a factor of 10) to reduce down to 100 kHz of bandwidth.

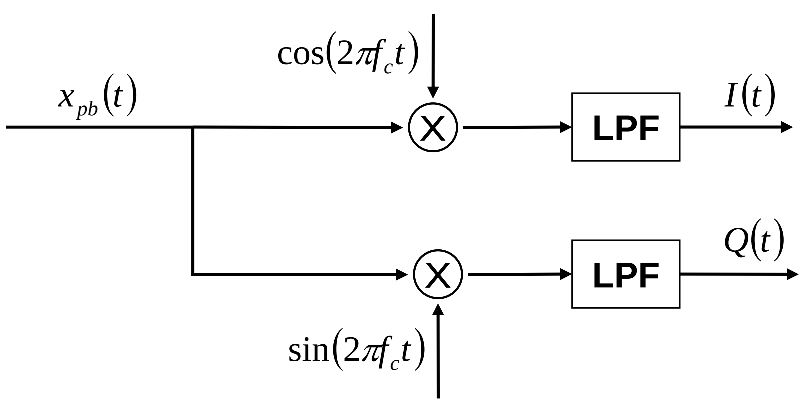


**Figure 9: I&Q Demodulation.**

The I&Q demodulation or down-conversion operation requires a large number of multiplications (2 per data sample) plus the calculation of the sine and cosine terms. The low-pass filtering adds additional multiplications and additions (filter order multiplications and additions per data sample).

Also, the filter has a delay equal to the number of taps or filter coefficients. The filter needs to "fill up" and then stay filled up; resetting the filter to zeros at each new buffer of data would cause discontinuities (jumps) in the data. Thus, the filter state needs to be preserved between buffers of data, adding to the complexity. However, we have made use of the following facts to reduce the number of calculations, reduce complexity, and improve performance:

- The data will be decimated by a factor of 10 so only every 10th sample needs to be calculated.
- If the filter length is equal to the decimation then the filter delay products will not need to be saved due to the decimation.
- At 1MHz sampling and 100kHz carrier, cosine, sine are periodic every 10 samples so only 10 sine, cosine coefficients are needed.

Various types of $9^{th}$ order FIR filters were examined in Matlab. The one that seemed to have the best performance and the simplest coefficients (no round-off error) is a simple Moving Average filter with all coefficients equal (set to 0.1 to keep unity gain). The filter frequency response is shown in Figure 10 and a close up in Figure 11.

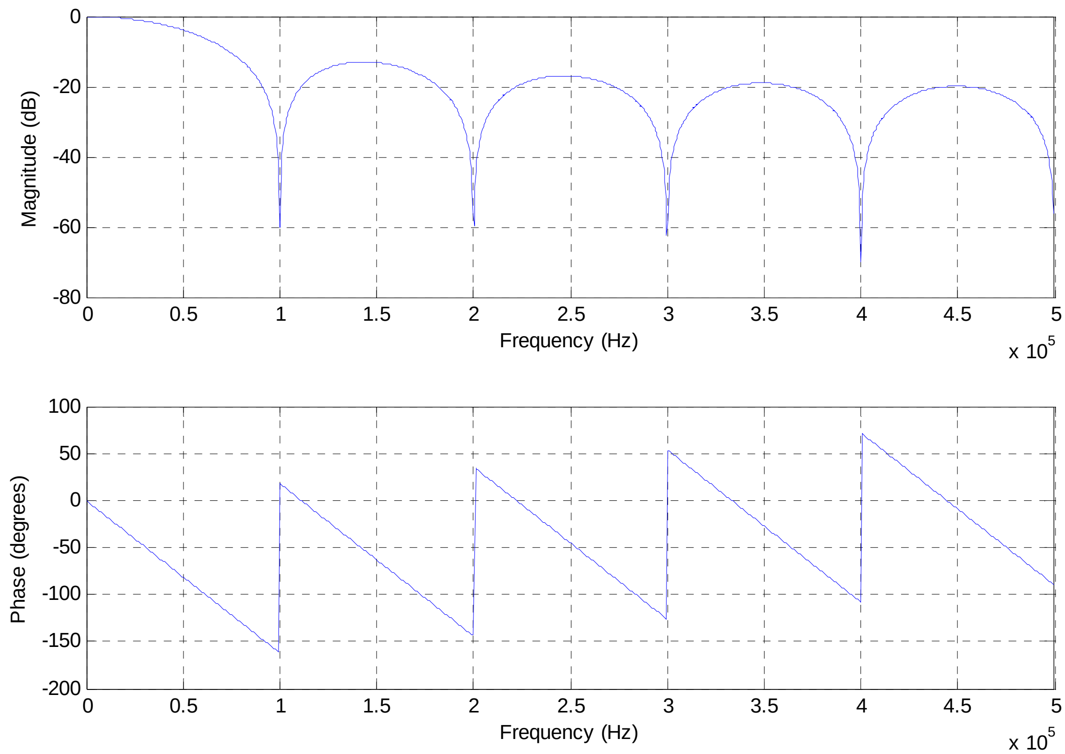


**Figure 10: $9^{th}$ Order FIR Filter Response.**

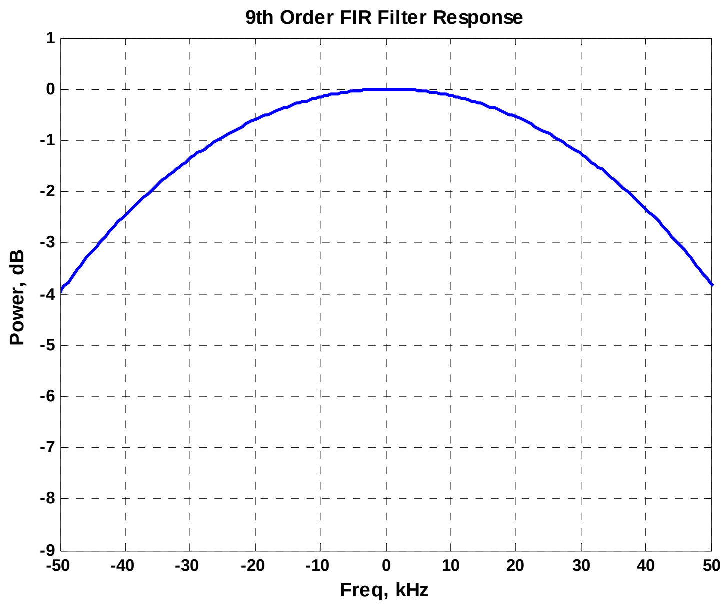


**Figure 11: Filter magnitude response over -50 to 50 kHz region.**

# Software

The final component of the LDaC system is the software. A custom C++ application was developed by Alion. This application is shown in Figure 12. A variety of options are user selectable.

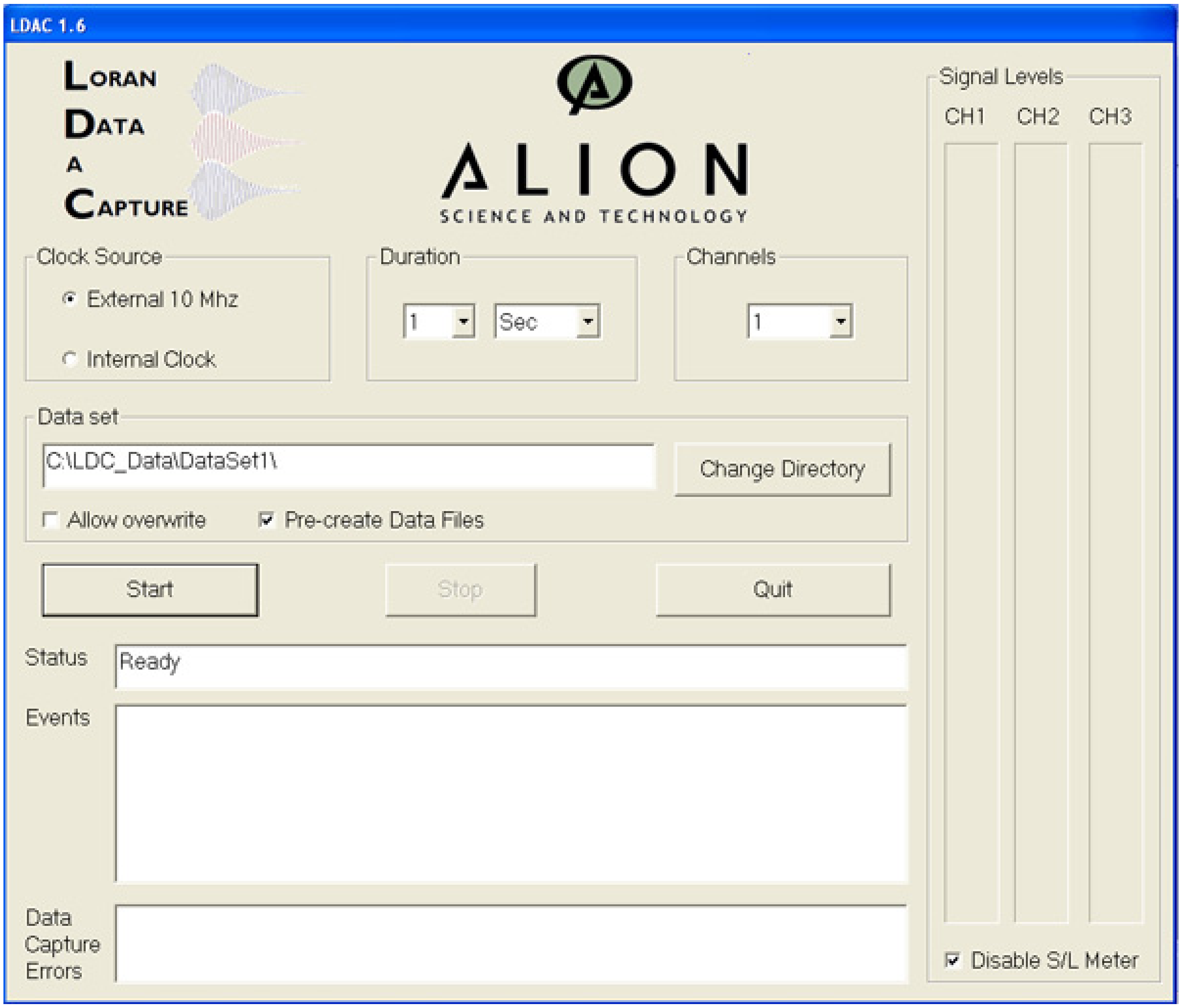


**Figure 12: LDaC Program Window.**

### Clock Source

Either an external clock source can be provided or the internal clock (on the A/D board) can be used. It is recommended that a stable and accurate external clock reference such as a Cesium or Rubidium frequency standard or a 10 MHz output from a GPS receiver be used as the internal clock is not that stable.

### Collection Duration

The desired duration of the collection period (time value of 1,3, 5 or 10 and units of sec, min, or hours) is set using the drop-down boxes in the **Duration** pane. By default the software will record only one data sample. Data will be recorded in one second intervals for the duration that is specified. If the data collection interval is unknown, a large duration can be set as the data collection can be stopped manually at any time.

### Channels

The system can record data from 1, 2, or 3 channels. This allows the use of an E-field antenna (1 channel) or an H-field antenna (2 channels, one for each separate loop) or both. The desired number of channels is set using the drop-down box in the **Channel** pane.

### Directory

The directory structure for each data collection run can be specified. The root directory for the data set is specified in the **Data Set** pane. All data files and program execution log files will be saved into this directory. A new directory name can be typed directly in the text box, or the "Change Directory" dialogue can be used to navigate to the desired folder (Figure 13). The data will be broken up within this root directory into sub-directories by hour (hour one in folder "01", hour two in "02" and so on). The log file will be stored directly in the data directory.

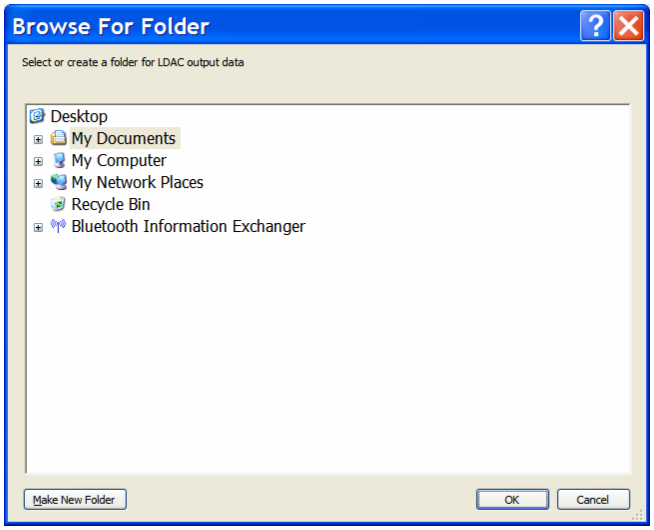


**Figure 13: Browse-For-Folder Dialogue seen with the "Change Directory" Button.**

One option provided by the LDaC program is to overwrite data that exists within the specified directory, if any. This is toggled by the "Allow Overwrite" checkbox under the directory text box. The software by default will not allow you to start data collection in a directory that already contains LDaC data. If this occurs, an error message will appear.

Another option provided is to allocate the data space before data collection occurs. This is an important option because there is a chance that, without pre-allocation, the data writing process might lag due to processing overload, causing missing samples. Checking this option allows the program to use the asynchronous write feature of Windows.

### Execution

Data collection is started by clicking on the **Start** button. The status bar and text boxes below will display the current sample being collected as well as related log and error messages. When data collection has commenced, it can be stopped either by waiting for the specified time duration to elapse, or by pressing the **Stop** button. While data collection is underway, the input signal levels can be monitored in the meter bars located on the right-hand side of the program window, as long as the checkbox labeled **Disable S/L Meter** under the bars is un-checked. The input gain should be adjusted so that signal levels on all channels are around 90% of peak; higher signal levels will cause data clipping, and lower signal levels will result in poor data resolution.

**Data File Format**

The LDaC program creates a binary data file for each second of data. The files are sequentially named starting at "iq000001.iqd" and placed in the directory specified by the user.

Each data file contains the 100 kHz in-phase (I) and quadrature (Q) data for each channel selected, stored as 16 bit integers. The file contains the 100,000 16-bit in-phase integers of the first channel followed by the 100,000 16-bit quadrature integers of the first channel. If more than one channel is recorded, the other channels are also stored consecutively in the same format as channel one. If the user is storing only one channel, the file size is about 390 kb each second. Two channels produce about 780 kb, and three channels produce about 1170 kb file sizes. The actual size of the data files will be larger than the size of the data stored within them as the program pads the end of the file with 0's up to the next multiple of the hard disk sector size.

The following tables summarize the file formats.

**Table 1. LDaC File Format for One Channel of Data.**

| Channel | Data | Size | Type |
|---|---|---|---|
| One | I | 100,000 | 16 Bit Integer |
| One | Q | 100,000 | 16 Bit Integer |

**Table 2. LDaC File Format for Two Channels of Data.**

| Channel | Data | Size | Type |
|---|---|---|---|
| One | I | 100,000 | 16 Bit Integer |
| One | Q | 100,000 | 16 Bit Integer |
| Two | I | 100,000 | 16 Bit Integer |
| Two | Q | 100,000 | 16 Bit Integer |

**Table 3. LDaC File Format for Three Channels of Data.**

| Channel | Data | Size | Type |
|---|---|---|---|
| One | I | 100,000 | 16 Bit Integer |
| One | Q | 100,000 | 16 Bit Integer |
| Two | I | 100,000 | 16 Bit Integer |
| Two | Q | 100,000 | 16 Bit Integer |
| Three | I | 100,000 | 16 Bit Integer |
| Three | Q | 100,000 | 16 Bit Integer |

## System Verification

A number of tests were run on the system to verify that it was operating as designed. The procedure to characterize the response of the LDaC system was to sweep the input of the LDaC using the source on an Agilent 89410 vector signal analyzer. The LDaC system was run and the resulting data plotted in Matlab. All three channels were tested but since the results were identical across the three channels (as it should be) plots for only one channel are shown here.

The first test was to directly connect the 89410 to the input of the A/D board. A chirp source was used in the frequency range from 0 to 500 kHz (since the A/D board samples at 1 MHz, 500 kHz is the maximum frequency to prevent aliasing). The frequency was swept 0-500 kHz over 1 second. The source signal level was 13dBm. A flat response across the 50-150 kHz bandwidth is seen (Figure 14).

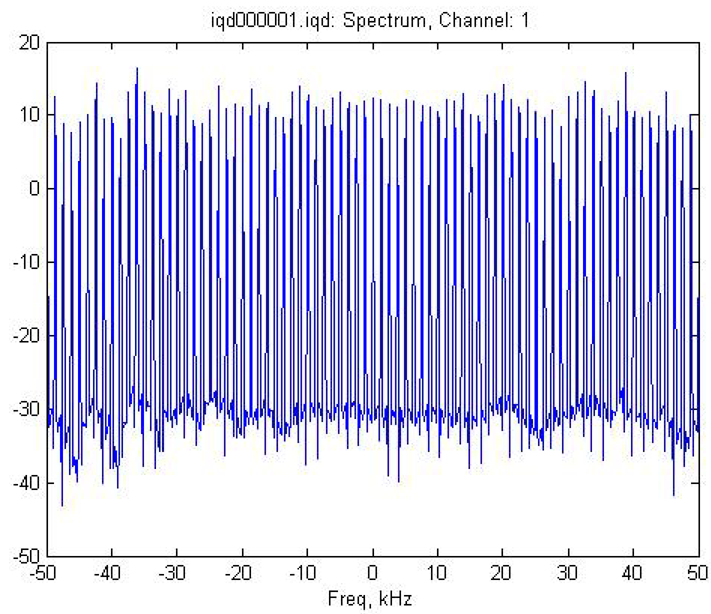


**Figure 14: Frequency response plot of a 1 sec. frequency sweep of the LDAC, using a 0-500kHz chirp signal at 13dBm.**

The second test was to change the frequency sweep to 50-150 kHz to match the output of the analog bandpass filters. The frequency sweep signal tends to have some undershoot/overshoot at the ends of the frequency range. The 9$^{th}$ order LP filter response can be seen in the roll-off to a 4 dB attenuation at ±50 kHz (Figure 15).

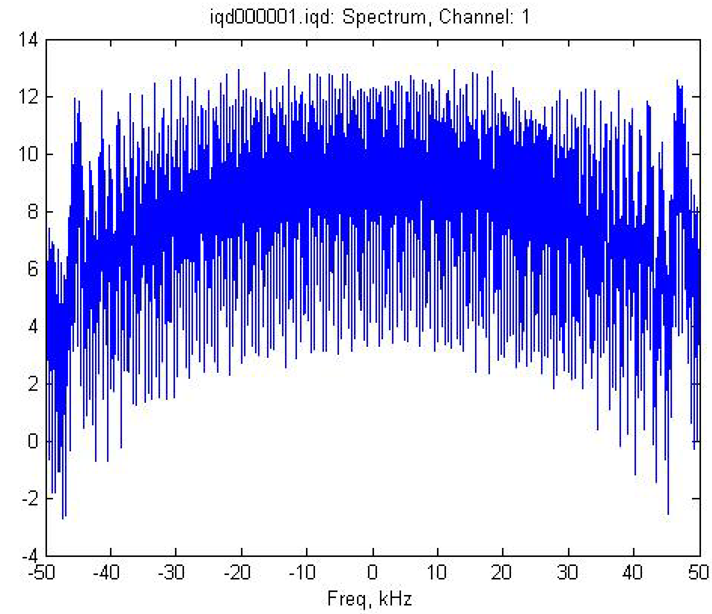


**Figure 15: Same as Figure 14, but with a 50-150 kHz chirp signal..**

The third test was to pass the 0-500 kHz frequency sweep through the analog bandpass filter prior tothe LDaC system; a test of the complete system. This response is shown in Figure 16for a source level of 10dBm. The LDaC response has ~11dB loss due to the I&Q demodulation and decimation. The system has a ~6 dB loss due to the analog bandpass filter.

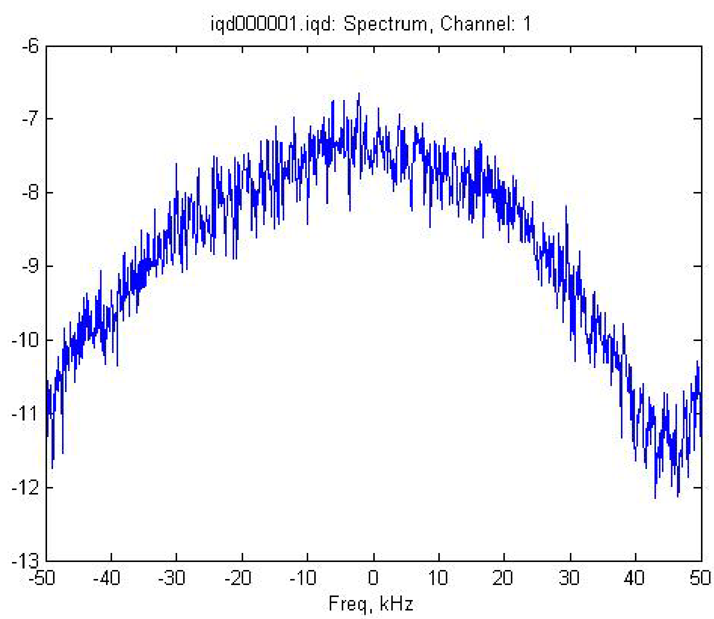


**Figure 16: Magnitude response of complete LDaC system. The 4 dB FIR filter rolloff is evident.**

# Conclusions

A wide-band Loran data acquisition system has been successfully designed and implemented. The LDaC System meets the design goals of a wide bandwidth (100 kHz), multi-channel (3 channels), low cost (off-the-shelf components), open data file format, and the design is freely available. The system was tested and the performance verified. It has been used to so far to support analysis of 9$^{th}$ pulse Loran data channel performance and Loran Drive Waveform testing. It is also being used for P-static testing at FAATC.

# Acknowledgments

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# Disclaimer and Note

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, or any agency of the U.S. Government

# Biographies

Dr. Gregory Johnson is a Senior Program Manger at Alion Science & Technology. He heads up the New London, CT office which provides research and engineering support to the Coast Guard Academy and R&D Center. Recently he has been working on projects in Loran, DGPS and WAAS. Dr. Johnson has a BS in Electrical Engineering from the USCG Academy (1987), a MS in Electrical Engineering from Northeastern University (1993), and a PhD in Electrical Engineering from the University of Rhode Island (2005). He has over 17 years of experience in electrical engineering and R&D, focusing on communications, signal processing, and electronic navigation and has published over 35 technical papers. Dr. Johnson is a member of the Institute of Navigation, the International Loran Association, the IEEE (Institute of Electrical and Electronics Engineers), and AFCEA (the Armed Forces Communications Electronics Association). He is also a Commander in the Coast Guard Reserves.

Mr. Ruslan Shalaev is a Software Engineer at Alion Science and Technology. He develops custom software for Alion Science clients, and performs internal development for needs of data collection. Mr. Shalaev current and recent projects include developing ReceiversIntegration software that facilitates Loran ASFs field data collection, Loran Long Term Seasonal Monitors Clients/Servers network that is now integrated with Loran 9'th pulse corrections, Loran Data Capture System, DGPS Field Strength Prediction. In addition, he works on processing and analysis of data collected in the field by Alion team, and comparison of measured data with predicted values using ASF modeling software such as BALOR. Mr. Shalaev has BS degree in Computer Science from Binghamton University.

Mr. Michael Kuhn is an engineer at Alion Science and Technology, having worked part-time for them for over two years. He graduated from the University of Rhode Island with a BS in Electrical Engineering, and is continuing his education in the graduate program there. His concentration is digital signal and image processing, and communication systems.

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