Lockheed Martin Aeronautics Company

WIRELESS SENSORS FOR AGING AIRCRAFT THEALTH MONITORING

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PURPOSE

The purpose of this paper is to describe the set-up, procedure, and results of a test accomplished to verify the viability of *Bluetooth* Wireless Technology for Prognostic Health Management (PHM) applications. The test was performed at Lockheed Martin Aeronautics Company, Fort Worth, TX, May 24, 2000, at Run Station 15, on an F-16B test aircraft, serial number 6282. Internal support for the test was covered by the LM Aero Flight Test group, F-16 Maintainability group, F-22 Maintainability group, JSF Maintainability/PHM group and EMI/EMC engineering. Jens Hult and Andy Rabiner from Oceana Sensor Technology (OST), provided external support and Leo Fila from CENTRA Technology whom observed the test for Dr. Bill Scheurun of JSFPO/DARPA.

This test was performed to evaluate a prototype wireless communication technology offered by OST. *Bluetooth* Wireless Technology has never been tested in any environment as electrically demanding as a military fighter aircraft. This test was performed to support the presumption that *Bluetooth* Wireless Technology could operate within normal parameters in this electrically dynamic environment while not interfering with aircraft subsystems.

Potential applications of *Bluetooth* Wireless Technology in the aerospace industry are endless, including; developmental testing, manufacturing, PHM, ground support equipment, data transfer and active control. This test provided an indication of the applicability of *Bluetooth* Wireless Technology to aerospace and military applications. Furthermore, the test allowed OST to better identify where improvements may be incorporated in order to be the most effective in meeting these needs.

1.0 INTRODUCTION: BLUETOOTH WIRELESS TECHNOLOGY

1.1 HISTORICAL BACKGROUND

In 1998 a group was established to manage the new communication technology. This became known as the Special Interest Group (SIG) of *Bluetooth* Wireless Technology. The intent was to create an open specification (e.g. a global industry standard) for a short-range, cable replacement, radio technology for use in the mobile and business market segments. The *Bluetooth* SIG is led by a nine-company promoter group including 3Com Corporation, Ericsson, IBM Corporation, Intel Corporation, Lucent Technologies, Microsoft Corporation, Motorola, Inc., Nokia, and Toshiba Corporation. The Bluetooth SIG today consists of approximately 1900 companies worldwide. Market researchers at Cahners In-Stat Group estimate that by 2005, *Bluetooth* Wireless Technology will be a built-in feature in more than 670 million products.

1.2 TECHNOLOGY IN BRIEF

Bluetooth Wireless Technology is a short-range, battery powered, digital spread spectrum radio link and communication protocol intended to replace the cable(s) connecting portable and/or fixed electronic devices (i.e. sensors). Key features are small size/low weight, robustness, low complexity, low power, and low cost.

This Wireless Technology operates in the unlicensed ISM (Industrial Scientific Medical) band at 2.4 GHz. A frequency hop transceiver is applied to combat interference and fading. A shaped, binary FM modulation is applied to minimize transceiver complexity. The gross data rate is 1 Mbit/s. A slotted channel is applied with a nominal slot length of 625 ms. For full, asynchronous, duplex transmission, a Time Division Duplex (TDD) scheme is used. On the channel, information is exchanged through packets. Each packet is transmitted on a different hop frequency. Advanced error-correction methods, as well as encryption and authentication routines protect all data for user's privacy.

Bluetooth Wireless Technology supports both point-to-point and point-to-multipoint connections. A sensor equipped with a *Bluetooth* radio establishes instant connection to another *Bluetooth* radio as soon as it comes into range IF both radios have approved the authentication procedure. Several piconets can be established and linked together ad hoc, and all sensors in the same piconet are synchronized.

Typical transmit power is 1 mW, which reliably communicates over a range of approximately 10 meters, but a version with 100 mW transmit power will be available for applications where longer range, up to 100 meters, is needed. In either case, transmit power is dynamically controlled and adjusted during transmit cycle. A *Bluetooth* radio limits the output power to the amount actually needed. If, for instance, the receiving radio indicates that its received signal strength is outside the optimized value range, the transmitter immediately modifies its signal strength to suit the environmental conditions.

2.0 TEST SET-UP

The test set-up consisted of a two-phase schedule. Each phase is described below.

2.1 PHASE I

Phase I utilized two *Bluetooth* radio circuit boards hardwired to a laptop computer (see Figure 1). The laptop was used to perform specific software operation checks by sending hex bit coded words to *Bluetooth* board A, and then verifying the signal integrity through *Bluetooth* board B. The signal integrity was verified through the use of bit error rates (BER%) and parts per million bit error rate (PPMBER). In a normal, non-interference, environment the BER is 0%, and the PPMBER is 0.0. Phase I consisted of several test configurations.

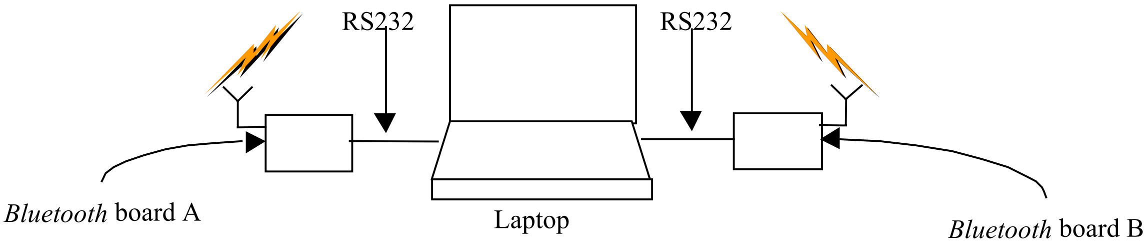


Figure 1: Phase I Setup

The initial test configuration had *Bluetooth* board A in the left side hydraulic quick access door (door 3413), and *Bluetooth* board B in the aft electronic equipment bay behind the right side (panel 2204). *Bluetooth* board B remained in this location for the remainder of the test. *Bluetooth* board B as installed is shown in Figure 2. Approximately 12 feet, numerous avionics boxes and bulkheads separated the two Boards. Communication between the two *Bluetooth* boards was NOT possible in this configuration.

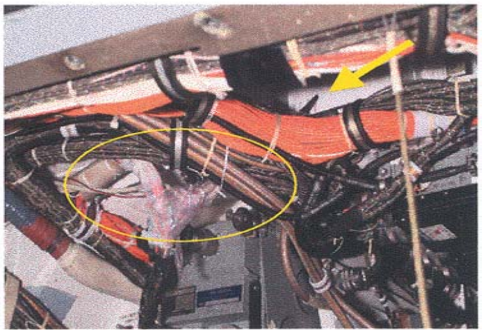


Figure 2: Board B in Aft Equipment Bay. Antenna tip is visible in top of photo.

In the second configuration, *Bluetooth* board A was moved to the right side electronic equipment bay under panel 2206. This panel is shown open with the RS232 hardwire extruding from the aft equipment bay to the laptop in Figure 3. This location separated the *Bluetooth* boards by approximately two feet, multiple harnesses, and one bulkhead. The aft equipment bay was closed and sealed, and the bay containing *Bluetooth* board A was fastened and not sealed. It was in this configuration that we accomplished all the EMI/EMC testing reported below in the test procedure. Wireless communication between the Boards was successful in this configuration.

Figure 3: Location of Board B in configuration 2

The third and fourth configurations consisted of relocating *Bluetooth* board A under panel 1202 to the forward electronic equipment bay, then under panel 2417 to the left side of the aft equipment bay. The *Bluetooth* boards maintained good communications in both of these configurations.

2.2 PHASE II

Phase II utilized a *Bluetooth* board with a sensor attached as shown in Figure 4. The sensor utilized was a TMP37F thermocouple on a 3-foot wire, hardwired to a *Bluetooth* board. The sensor package was completely wireless and did not involve the use of the laptop computer. A Palm Pilot with a modified *Bluetooth* modem and antenna was used to receive the temperature data transmitted by the Board. Figure 5 shows the *Bluetooth* board & sensor used.

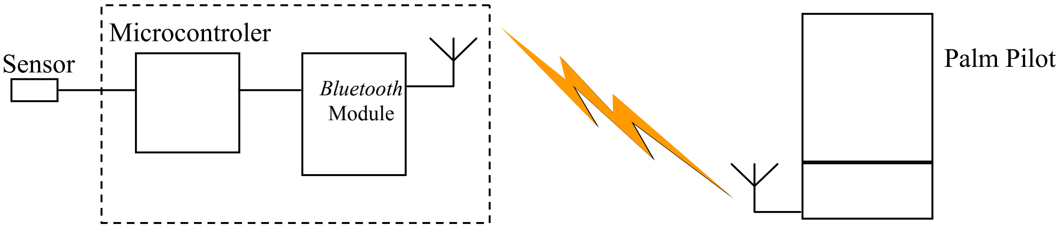


Figure 4: PHASE II setup

The *Bluetooth* temperature sensor package was located in various locations around the fuselage. The board had no problems communicating the temperature data to the Palm Pilot when not transmitting through the fuselage. The accuracy of the thermocouple was not confirmed. The temperatures measured were used to demonstrate the capability of the *Bluetooth* board to receive data from an arbitrary sensor and transmit them to the Palm Pilot. While the *Bluetooth* sensor package was installed in the aircraft, test engineers moved around the airplane and were able to receive the data consistently up to 18 feet away.

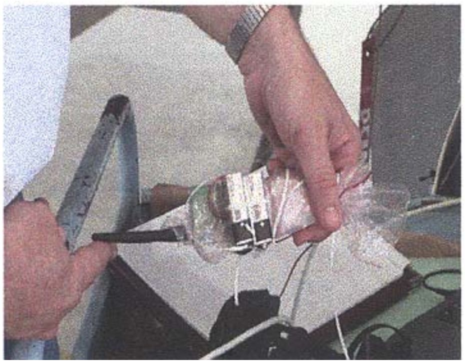


Figure 4: Bluetooth wireless board with thermocouple attached

3.0 TEST PROCEDURE

3.1 PHASE I

Most of the test was performed in Phase I, in the second test configuration, (*Bluetooth* board A located in the right side in the aft electronic equipment bay; *Bluetooth* board B installed on the right side of the fuselage, in the bay directly behind the aft equipment bay.) The benefit to using the Phase I test setup was the ability to quantitatively monitor signal integrity between the two *Bluetooth* wireless boards. After communication had been established between the two boards various subsystems were activated in a specified order and the signal quality was monitored and recorded. Interference or transient responses could be observed in a real-time plot of Bit Error Rate with respect to time. The details of the results will be covered in the next section.

A modified EMI/EMC Safety of Flight test plan was performed. Engine power was unavailable precluding use of flight surfaces, however, a relatively through electronic test sequence was completed and is described in detail.

The test procedure included five Runs. In each Run specified systems were activated in sequence and the *Bluetooth* signal quality was monitored for response to that system. Table 1, shown below, is a detailed breakdown of each Run and what sub-systems were activated, and in what sequence. Error correction algorithms/methods were not utilized for this test.

Mike Jaxion was in the cockpit operating the controls, Michael Bawden and Jens Hult were operating the *Bluetooth* boards and laptops and recording the signal integrity data, and Michael Gandy was coordinating between them and taking test operation notes.

	RUN #1	**RUN #2**	**RUN #3**	**RUN#4**	**RUN #5**
Main Power	X	X	X	X	X
Ext. Cooling	X	X	X	X	X
TACAN			4		
ILS				1	
UHF			1		
VHF			2		
Back-up UHF			3		
HUD				2	
FCC		2			
SMS					1
MFD		4			
Up-Front Cont.		5			
INS		3	NAV	NAV	NAV
IFF				3	
CADC		1			
DTE					2
Radar altimeter					3
Radar					4

notes:
1. Numbers are in sequence of activation.
2. X - Indicates that systems were on.
3. Subsystems were turned on and left activated.

Table 1: Test sequence for each Run

3.2 PHASE II

The phase II test procedure was less structured than Phase I, due to the flexibility of the test set-up. The independent *Bluetooth* wireless temperature device was placed into various bays throughout the airframe. Each location had the bay closed and sealed. With each location the ability to monitor temperature data was verified up to 18 feet.

Phase II was being performed simultaneously with Phase I, however, sub-systems that were being activated/deactivated at the time of each location, were not recorded. This test procedure would simulate maintenance personnel recording maintenance data independently with what was being done with the aircraft's sub-systems.

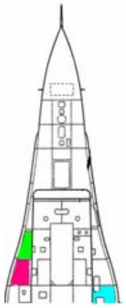
4.0 TEST RESULTS

The results of this test are given in terms of Bit Error Rate (BER) as a percentage. A theoretically perfect signal has a BER of 0%. The average BER experienced throughout this test was between 0% and 0.4%. This BER would be of minimal concern to sensor data transmission signal integrity, and probably would not even register when correction algorithms/methods are utilized.

This *Bluetooth* Wireless Demonstration was performed in two phases, as described above. The results of each phase will be presented in the following sections.

4.1 PHASE I

Each test Run for Phase I will be discussed and the data recorded will be presented. Some sample data is plotted and presented in Appendix A. Where a run was too long to be recorded on a single plot the graphs are labeled with alphabetical designations. Notes on each run are included in the appendix.



In the first test configuration, (i.e. Bluetooth board A in the LEFT side hydraulic quick access door (door 3413) and Bluetooth board B in the RIGHT side aft electronic equipment bay, behind sealed panel 2204). The devices were separated by numerous bulkheads and were on opposite sides of the aircraft. We were unable to establish wireless communication in this configuration. The most reasonable explanation was the low power (1 mW) of this preliminary design. For the following test configuration the boards were moved to the left side of the aircraft, and, were separated by ONE bulkhead (containing lightening holes) and several wiring harnesses.

For the second test configuration, communication between the *Bluetooth* boards was established. The ability to transfer files, and verify signal integrity was confirmed. Main Power and External Cooling were activated on the test aircraft. The responses that were detected by the *Bluetooth* boards can be observed in a separate data file.

Run#2 was performed twice. The results of the first run are shown in a separate data file. The specified electronic subsystems were activated simultaneously and it was not possible to determine which subsystem was causing the disturbances observed. As the result graph shows there was a relatively large transient response for approximately 30 seconds. *Bluetooth* signal integrity was confirmed and the ability to transfer files between the boards was established between each Run with the subsystems activated.

The second time that Run#2 was performed, the subsystems were activated individually and the response to each system was documented. The transient responses due to each system can be clearly identified in **Figures A2.1a and A2.1b**. The inertial navigation system (INS) takes eight minutes to fully "spin" up. The continuing disturbance exhibited in Figure A2.1a is most likely the result of this spin up period. The INS effect begins at item 3 and continues contributing throughout the remainder of that Run. We waited for approximately 8 minutes after this run to allow the INS to come to steady state.

In Run#3 the INS was switched to NAV, the aircraft's communication radios and TACAN were activated. The radios observed were the UHF, VHF, and the backup UHF radio. The data exhibited a transient response for approximately 10 to 15 seconds and then came to stead-state. The microphone was not keyed during this test. This data is exhibited in a separate data file.

In Run#4 and Run#5 the remaining systems were activated. The transient responses due to equipment activation observed in earlier Runs were less evident from this point on as can be seen in a seprate data file. Between each test run, the ability to transfer files and dynamic data between the two *Bluetooth* boards was established. From this point onward we were unable to pick up transient responses due to the activation and deactivation of aircraft systems.

One very important aspect of the test was the inability to reproduce the transient responses due to the F-16B electronic subsystems. Towards the end of the test, past Runs were revisited and we could not reproduce the transient responses that were observed earlier. This occurred toward the end of the test, after the electronics had been on for quite some time. After Run#5 was performed, all equipment except main power and external cooling were deactivated. Then Run#2.0 was duplicated. This time we observed no further transient response due to the activation of the aircraft subsystems.

Several ideas have been presented to explain why the results could not be repeated. The first is that the electronic systems on-board the F-16 have capacitance charging time. During the charging time the electronics are changing the characteristics of their response. After the charging time, they have reached their steady state operation. A second explanation is that the F-16 subsystems RF signals were actually interfering with the circuitry in the *Bluetooth* boards, not necessarily with the *Bluetooth* RF signal transmission. As shown in Figure 4, the *Bluetooth* boards were completely un-shielded from the outside RF world. The third explanation proposed is that the *Bluetooth* boards internal RF filters were compensating for the interference. Once compensated, the *Bluetooth* boards were then able to communicate amongst themselves uninterrupted. These questions require further testing to answer. Possibly a EMC/EMI anechoic chamber should be utilized to isolate the variables.

4.2 PHASE II

Bluetooth Wireless Technology was successful in Phase II. The thermocouple temperature sensor was transmitting data from behind sealed doors. The *Bluetooth* set-up was able to transmit the data up to 18 feet from the source through the sealed aircraft skin.

Communication was NOT successful when transmitting through opposite sides of the aircraft. This is something that hopefully will be improved upon with future versions of *Bluetooth* Wireless Technology.

In general the test was successful. We were able to establish wireless communication between the *Bluetooth* boards. While connected, data files could be transferred between *Bluetooth* Boards and real time dynamic data could be observed. Mike Jaxion, the participating EMI/EMC expert, reported, “no EMC related anomalies were observed”. Mike Jaxion was the engineer activating the F-16B electronic subsystems and looked for usual anomalies from inside the cockpit. JSF PHM design engineer, Brent Anderson stated, “The testing that was accomplished …… exceeded my expectations”. The specialist engineers from OST were very excited about the results. Bluetooth Wireless Technology is in a preliminary design phase and no other testing of this magnitude has been performed to date.

5.0 CONCLUSION

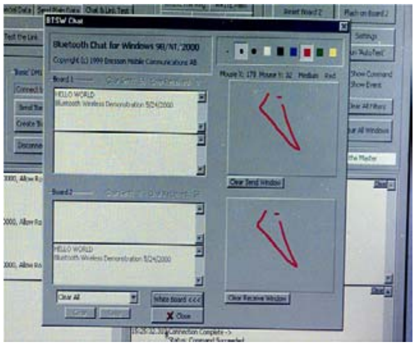
The purpose of this test was to determine if there was any EMI/EMC interference with the F-16B sub-systems, and to determine if dynamic sensor data could be transmitted real time, wirelessly from within the airplane. The results for both of these objectives were favorable. The test also identified some key areas in which design improvements could be made to tailor this technology to the aerospace industry. One of the recommended improvements was to increase the output power from 1mW to 100mW. This would increase the reception distance and improve communications between multiple bulkheads. Other suggestions included a more RF friendly package for the *Bluetooth* boards. This might reduce possible RF interference that the *Bluetooth* boards could be experiencing.

Other future development goals that were suggested were various applications of *Bluetooth* Wireless Technology to smart sensors. Smart sensors are sensors that in addition to containing the actual sensing element also include all necessary signal conditioning and processing hardware and software, providing them the ability to “know” when acceptable parameters have been violated. These sensors could eliminate the need for a sensor wire to be run to an external-processing computer. Of course, the next step would be to test *Bluetooth* Wireless Technology in such a manner that the sensor could wirelessly transmit it’s data to a central maintenance or control unit on-board the aircraft.

With all the EMI/EMC dynamics existing on a modern aircraft, the smart sensor with *Bluetooth* Wireless Technology*,* could sense an imminent failure and then “wake-up” to start sending prognostic/diagnostic data. This would save the battery life and would preclude continuously sending RF data throughout the aircraft. The sensors could even store the failure data until the end of flight, at which time the sensors would report its data to the maintenance control computer.

If *Bluetooth* Wireless Technology can be integrated with smart sensors, it would be possible to completely redefine future maintenance concepts. It would be possible to unobtrusively, retrofit legacy aircraft with wireless PHM systems. There could be a wireless failure prediction system throughout the aircraft, and failure data could be wirelessly transmitted off the aircraft into the ground based logistics infrastructure. This data could then be trended over time in order to warn of eminent failures BEFORE the component actually fails in flight. Maintenance shops could be notified of incoming failed components and necessary parts could be automatically ordered from vendors via the internet.

An exciting aspect of this test is that *Bluetooth* Wireless Technology has never been tested to this challenging level before. Particularly not in an electronic/RF demanding environment such as a tactical military aircraft. Brent Anderson felt, after seeing the demonstration, that “the applications for (aerospace) industry are endless…..”. Discussions have been made to applications in wind tunnel testing, to manufacturing, Prognostic Health Management and smart sensors that could be easily retrofit to legacy aircraft. A small, self contained, wireless smart sensor could save money in retrofit design of legacy aircraft, and also simplify the wiring design of future aircraft. The applications truly are “endless”.


BTSW Chat

Bluetooth Chat for Windows 98/NT/2000

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Board 1

HELLO WORLD
Bluetooth Wireless Demonstration 5/24/2000

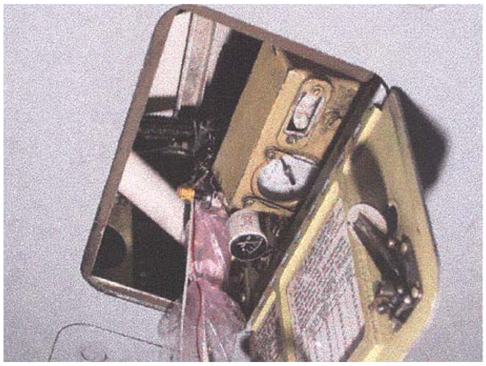
Board 2

HELLO WORLD
Bluetooth Wireless Demonstration 5/24/2000

Mouse X: 179 Mouse Y: 32 Medium Red

PICTURE 5: Example of how the two BT Boards can communicate with each other. Draw on one, and it transfers through the BT transceiver.

PICTURE 6: The modified BT Palm Pilot receiving temperature data. (Jens Hult) - Specialist Engineer



PICTURE 7: BT board with thermocouple located in the aircraft in Phase II.

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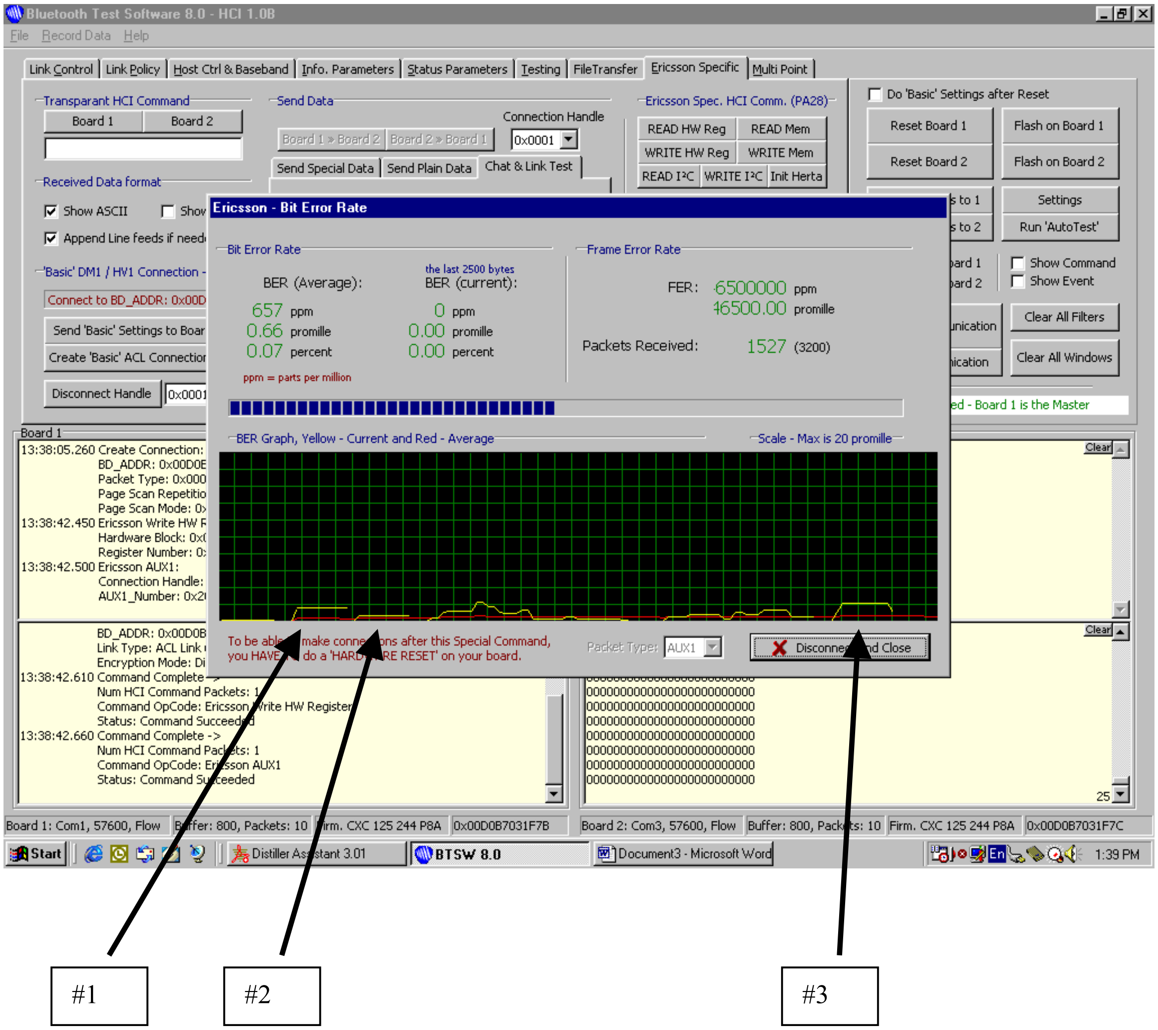
[1] BLUETOOTH is a trademark owned by Telefonaktiebolaget L M Ericsson, Sweden and licensed to Oceana Sensor Technologies, Inc.

APPENDIX A, Figure A2.1a, (SAMPLE OF DATA COLLECTED)



Ericsson - Bit Error Rate

Bit Error Rate

BER (Average):	the last 2500 bytes BER (current):
657 ppm	0 ppm
0.66 promille	0.00 promille
0.07 percent	0.00 percent

ppm = parts per million

Frame Error Rate

FER: 6500000 ppm
46500.00 promille

Packets Received: 1527 (3200)

To be able to make connections after this Special Command, you HAVE to do a 'HARDWARE RESET' on your board.

Connection Handle: 0x0001
Packet Type: AUX1

```
13:38:05.260 Create Connection:
             BD_ADDR: 0x00D0E
             Packet Type: 0x000
             Page Scan Repetitio
             Page Scan Mode: 0x
13:38:42.450 Ericsson Write HW R
             Hardware Block: 0x0
             Register Number: 0x
13:38:42.500 Ericsson AUX1:
             Connection Handle:
             AUX1_Number: 0x2
```

```
             BD_ADDR: 0x00D0B
             Link Type: ACL Link
             Encryption Mode: Di
13:38:42.610 Command Complete ->
             Num HCI Command Packets: 1
             Command OpCode: Ericsson Write HW Register
             Status: Command Succeeded
13:38:42.660 Command Complete ->
             Num HCI Command Packets: 1
             Command OpCode: Ericsson AUX1
             Status: Command Succeeded
```

ed - Board 1 is the Master

Board 1: Com1, 57600, Flow | Buffer: 800, Packets: 10 | Firm. CXC 125 244 P8A | 0x00D0B7031F7B
Board 2: Com3, 57600, Flow | Buffer: 800, Packets: 10 | Firm. CXC 125 244 P8A | 0x00D0B7031F7C

Start | Distiller Assistant 3.01 | BTSW 8.0 | Document3 - Microsoft Word | 1:39 PM

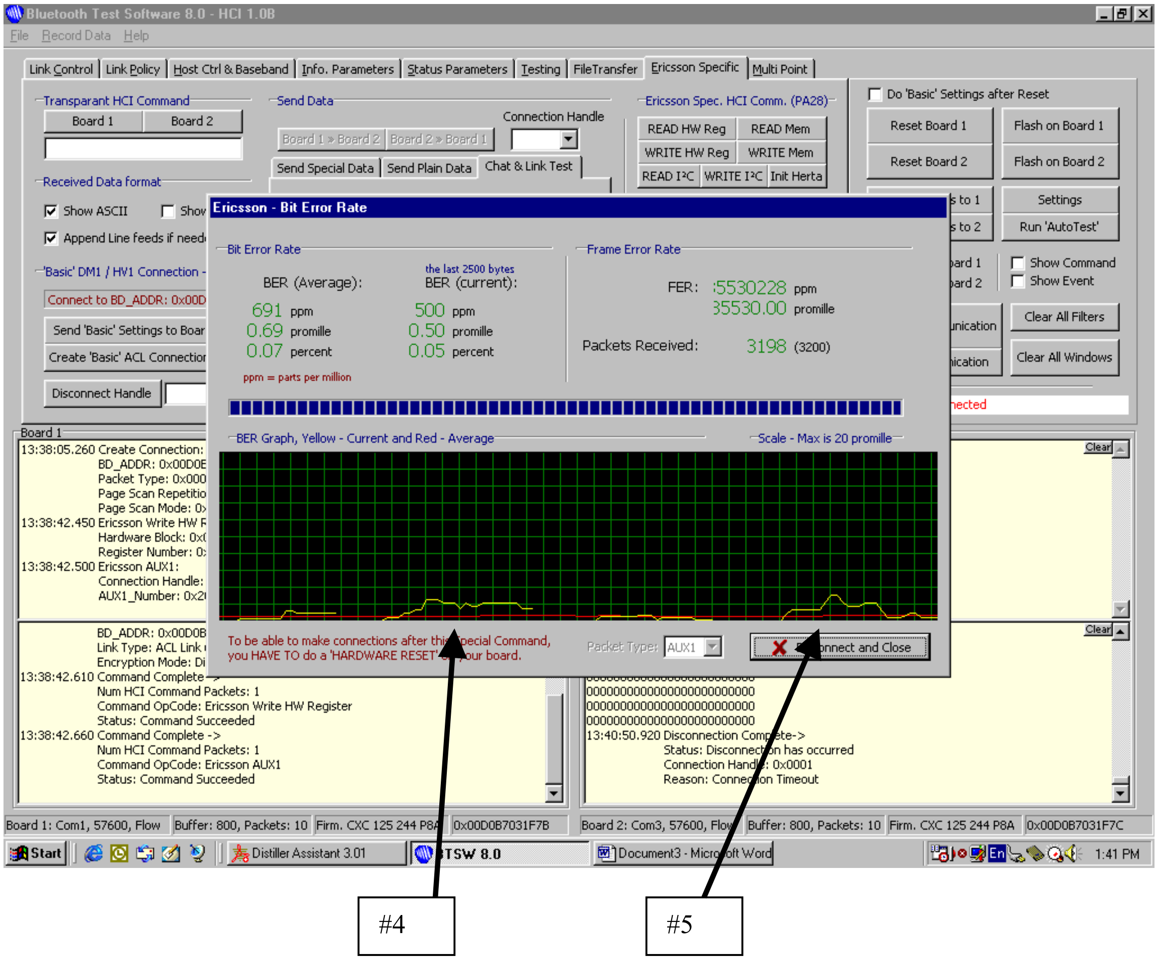
F-16 electronic Sub-Systems activated:

Item
1. CADC (Central Air Data Computer) (MAX BER ≈ 0.19%)
2. FCC (Fire Control Computer) (MAX BER ≈ 0.1%)
3. INS (Inertial Navigation System) (MAX BER ≈ 0.21%)

Notes:

1. Items #4 and #5 are shown in Figure A2.1b.
2. The prolonged transient response for the INS is suspected to be the INS “warm-up” phase for the first eight minutes.

APPENDIX A, Figure A2.1b, (SAMPLE OF DATA COLLECTED)



BER (Average):
691 ppm
0.69 promille
0.07 percent

the last 2500 bytes
BER (current):
500 ppm
0.50 promille
0.05 percent

ppm = parts per million

FER: :5530228 ppm
35530.00 promille

Packets Received: 3198 (3200)

To be able to make connections after this Special Command, you HAVE TO do a 'HARDWARE RESET' on your board.

```
13:38:05.260 Create Connection:
             BD_ADDR: 0x00D0E
             Packet Type: 0x000
             Page Scan Repetitio
             Page Scan Mode: 0x
13:38:42.450 Ericsson Write HW R
             Hardware Block: 0x0
             Register Number: 0x
13:38:42.500 Ericsson AUX1:
             Connection Handle:
             AUX1_Number: 0x2
```

```
             BD_ADDR: 0x00D0B
             Link Type: ACL Link
             Encryption Mode: Di
13:38:42.610 Command Complete ->
             Num HCI Command Packets: 1
             Command OpCode: Ericsson Write HW Register
             Status: Command Succeeded
13:38:42.660 Command Complete ->
             Num HCI Command Packets: 1
             Command OpCode: Ericsson AUX1
             Status: Command Succeeded
```

```
0000000000000000000000000
0000000000000000000000000
0000000000000000000000000
0000000000000000000000000
13:40:50.920 Disconnection Complete->
             Status: Disconnection has occurred
             Connection Handle: 0x0001
             Reason: Connection Timeout
```

Board 1: Com1, 57600, Flow | Buffer: 800, Packets: 10 | Firm. CXC 125 244 P8A | 0x00D0B7031F7B

Board 2: Com3, 57600, Flow | Buffer: 800, Packets: 10 | Firm. CXC 125 244 P8A | 0x00D0B7031F7C

F-16 electronic Sub-Systems activated:

Item

4. MFD (Multi-Function Displays) (MAX BER ≈ .25%)
5. Up-Front Controls (MAX BER ≈ 0.3%)

Notes:

1. Items 1, 2, and 3 were displayed in Figure A2.1a