

ELECTRONIC PROGNOSTICS – A CASE STUDY USING GLOBAL POSITIONING SYSTEM (GPS)

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Abstract- Prognostic health management (PHM) of electronic systems presents challenges traditionally viewed as either insurmountable or otherwise not worth the cost of pursuit. Recent changes in weapons platform acquisition and support requirements has spurred renewed interest in electronics PHM, revealing possible applications, accessible data sources, and previously unexplored predictive techniques. The approach, development, and validation of electronic prognostics for a radio frequency (RF) system are discussed in this paper. Conventional PHM concepts are refined to develop a three-tier failure mode and effects analysis (FMEA). The proposed method identifies prognostic features by performing device, circuit, and system-level modeling. Accelerated failure testing validates the identified diagnostic features. The results of the accelerated failure tests accurately predict the remaining useful life of a COTS GPS receiver to within ± 5 thermal cycles. The solution has applicability to a broad class of mixed digital/analog circuitry, including radar and software defined radio.

INTRODUCTION

Many types of circuits compose avionics systems. One of the following categories can be used to classify each circuit topology.

- High frequency analog
- Low frequency analog
- Low impedance
- High impedance

Common failure mode mechanisms for analog circuits depend largely on the architecture and relative operating frequencies of the circuit. In this paper, high frequency analog circuits are categorized as operating above 1GHz, while low frequency analog circuits operate below 1GHz. High frequency analog circuits are sensitive to small changes in device parameters,

resulting in non-destructive, or operational, failure modes. Unlike physical device failures, the cause of operational failures cannot be traced back to individual components. Low frequency analog circuits are more likely to undergo physical device failure. Fig. 1 illustrates the relationship between the operating frequency of an analog circuit and the different types of failure modes.

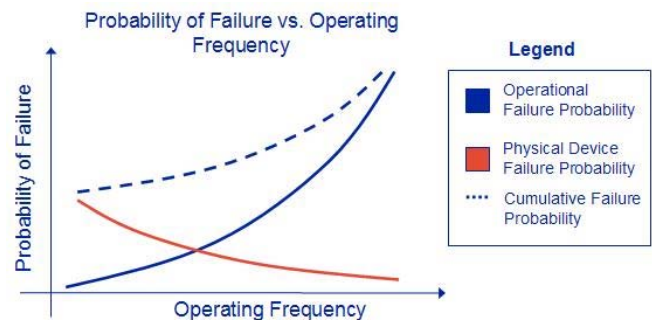


Fig. 1. Relationship between analog failure modes and operating frequency.

1. TARGET APPLICATION

Avionic systems containing high frequency analog circuits or RF circuits have high failure rates. Therefore, an avionics-related electronic system containing high frequency RF components was considered to test this theory. Evaluation of the following criteria led to the specific avionic system investigated in this report.

- Critical avionics subsystems
- Representative failure modes
- Thorough documentation
- Commercial availability for failure testing

One such avionics system that meets all selection criteria is the Global Positioning System (GPS). The Garmin GPS 15L-W, shown in Fig. 2, was selected for failure mode analysis and accelerated failure testing for the following reasons:

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- Thorough documentation
- Commercial-off-the-shelf (COTS)
- Embedded thermocouple
- Small form factor



Fig. 2. Garmin GPS 15L-W.

GPS BACKGROUND

The global positioning system (GPS) is a space-based radio-navigation system managed by the U.S. Air Force (USAF). GPS, originally developed as a military force enhancement system, supports the existence of two different services: the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). The PPS is reserved for military use and requires special PPS receivers to access the system, while the SPS is available to civilian users throughout the world. Fundamentally, both services operate on the same principles. Accuracy is the main difference between the two systems; the SPS provides a less accurate positioning capability than its counterpart [1]. All GPS systems consist of three major subsystems:

- GPS Satellites
- Transmission Paths
- GPS Receivers

The GPS constellation consists of 24 satellites in continuous operation with six additional backup satellites, each having an orbital radius of 26559.7 km [1]. All 24 satellites in the constellation are separated into six groups consisting of four satellites per group separated 60° apart with a maximum angle of inclination of 55° from the equator. Additionally, the satellites are designed to provide reliable service over a 7 to 10 year life time. Every active satellite broadcasts a navigation message based upon data periodically uploaded from the Control Segment (CS), which continuously monitors the reliability and

accuracy of each satellite. Therefore, this paper will focus on GPS reliability as a function of receiver degradation.

COMPONENT IDENTIFICATION

Identification of the critical components in the target application is required before any failure mode analysis is performed. A critical component is a discrete element, such as a single transistor, or a relatively complicated circuit, such as an RF mixer, that contains a relatively high probability (or risk) of failure. Fig. 3 and 4 present board layouts of the GPS receiver investigated. Table 1 provides a summarized reference of critical components with an associated number and color to identify the component name and circuit type.

FAILURE MODE ANALYSIS

A recent study of stand-alone GPS receivers that met Federal Aviation Administration TSO C-129 requirements found the probability of a receiver outage from a software-related problem is much greater than the occurrence of a total device failure [2]. To explain this phenomenon, a physical understanding of GPS receiver failure is required.

Failure mode analysis, starting at the device level, is essential to show that software failure modes manifest from small physical deviations in high frequency analog circuits. In failure mode analysis, circuit models are developed to simulate a circuit's performance when damage accumulates in discrete components. Monte Carlo simulation utilizes these device-level circuit models to analyze the changes in performance characteristics of the high frequency analog circuits. Then a system-level fault-to-failure progression model is developed based on changes in circuit performance characteristics. The identified features from the system-level model describe the fault-to-failure transition.



Fig. 3. Front side of GPS receiver.



Fig. 4. Back side of GPS receiver.

Table 1. Component Reference Table

No.	Circuit or Device	Circuit Type			
		Low Freq Analog	High Freq Analog	Low Impedance	High Impedance
1	Antenna		X		
2	Low Noise Amplifier		X		
3	Bandpass Filter		X		
4	RF Mixers		X		
5	Crystal Oscillator		X		
6	Digital Signal Processor				X
7	Flash Memory				X
8	Serial Driver				X
9	Serial Port				X
10	Voltage Regulator			X	

DEVICE ANALYSIS

The primary failure mode mechanisms in RF analog circuits occur within metal-oxide semiconductor field effect transistor (MOSFET) devices. Modern semiconductor devices consist of complimentary metal-oxide semiconductors, or CMOS technology, comprised of MOSFETs. As MOSFETs begin to age, the dielectric material of the device begins to degrade. The silicon dioxide bonds that form the dielectric break as a result of interaction between highly charged electrons, known as hot carriers [3]. In general, hot carriers are generated when the voltage between the gate and drain (V_{gd}) exceeds the voltage between the drain and source (V_{ds}), as shown in Fig. 5.

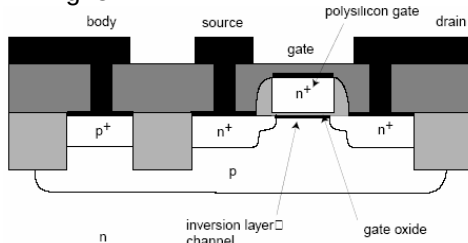


Fig. 5. Physical MOSFET layout.

Breakdown of the dielectric can lead to a failure mode known as Time Dependent Dielectric Breakdown (TDDB), which can gradually occur during normal operating conditions. Changes in a MOSFET's C-V and I-V device characteristics occur prior to TDDB [4]. Such deviations will alter the MOSFET's device performance parameters, including gain, transconductance, series resistance, and threshold voltage. Fig. 6 presents a model representing the changes in device parameters occurring after TDDB. The model introduces parasitic resistances and capacitances to mimic the damage accumulated during soft breakdown.

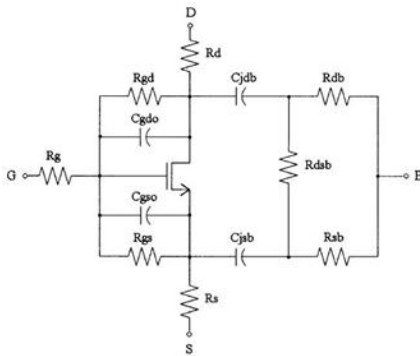


Fig. 6. MOSFET damage accumulation model.

CIRCUIT ANALYSIS

Many high frequency analog circuits, such as RF mixers and RF low noise amplifiers (LNA) are implemented using MOSFET devices. These circuits are sensitive to device variations at frequencies

exceeding 1 GHz. Therefore, variation in any device, either active or passive, can cause the following circuit characteristics to change:

- Phase response
- Frequency response
- Linearity
- Gain
- Impedance

RF mixers are composed of transistors and traditional passive devices including inductors, capacitors, and resistors. A Monte Carlo worst-case analysis was performed on a RF mixer circuit. The TDDB damage accumulation model, shown in Fig. 6, replaced the MOSFET devices in both circuits. The equivalent gate-to-source capacitance (C_{gso}) provided a damage accumulation parameter with a tolerance of 10%. Fig. 7 shows the results of the Monte Carlo analysis. The time domain phase of the RF mixer plots for ten different trials indicated an absolute maximum phase difference of 10%.

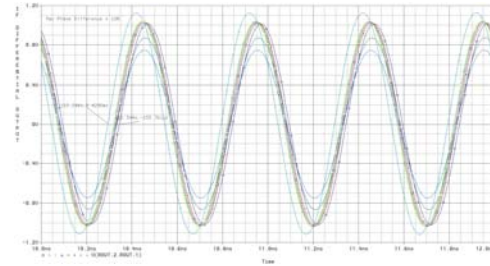


Fig. 7. Monte Carlo analysis plot of an RF mixer containing damaged MOSFETs.

SYSTEM ANALYSIS

Analyzing a sophisticated electrical system using a schematic can be rather complex. Instead, a system diagram can be used to model system functionality by representing the functionality of the electrical system. Fig. 8 shows a block diagram of a GPS receiver. A GPS receiver consists of three fundamental stages:

- Input stage
- Conversion stage
- Processing stage

These stages are very interrelated because of the complex nature of the GPS receiver. The input stage is the first stage in any GPS receiver. The front end of the input stage consists of an antenna and a RF amplifier. The conversion stage demodulates the incoming RF signal for data recovery. It consists of the demodulator, phase-lock feedback mechanism, and data recovery/reconstruction. In a basic binary phase shift keying (BPSK) system, the output from the RF amplifier is down-converted to a lower frequency or an intermediate frequency (IF) and mixed with quadrature LO signals. The composite

signal is then fed back to phase-lock to the carrier. Low pass filtering the outputs of one of the mixers recovers the data [4]. The data can be digitally processed once it is recovered from the RF signal. The digital processing stage recovers navigation messages by continuously synchronizing each satellite's gold code with the incoming data stream.

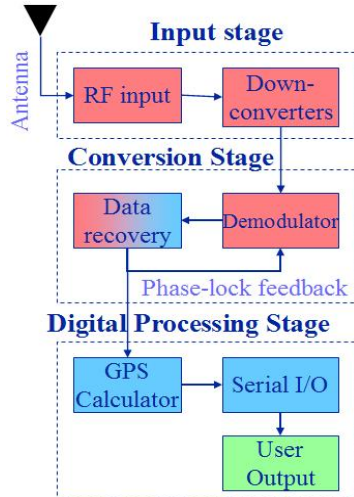


Fig. 8. Block diagram of a GPS receiver.

The overall reliability of a GPS receiver depends on the tolerance of each subsystem. The two largest reliability concerns include the LNA and the RF mixers. As shown earlier, changes in phase response, frequency response, impedance mismatching, and linearity were all attributed to device-level degradation of MOSFET devices. Consequently, synchronizing errors occur when the digital processing stage decodes the incoming data stream. The end result is a reduction in coverage of the GPS receiver which triggers two failure modes:

- **Precision Failure** – increased position error
- **Solution Failure** – increased outage probability

These failure conditions result in measurable parameters that change during failure progression.

FAILURE MODES AND EFFECTS

Failure mode, effects, and criticality analysis, or FMECA, is a method of analysis used to understand the root cause of failures, along with their relative probability of occurrence, criticality, and their effects on a system. The FMECA used for the GPS receiver provided a complete description of the fault-to-failure progression.

FEATURE EXTRACTION

A diagnostic feature is a system parameter (or derived system parameter) that is sensitive to the functional degradation of one or more circuits contained in the system. Diagnostic features can be used to predict the occurrence of an undesired system event or failure mode.

Direct measurements of diagnostic features are typically not feasible because they require advanced and usually impractical measuring techniques. However, system-level features, can provide valuable and easily obtainable diagnostic and prognostic information. For example, in a GPS receiver there are system-level features universal to all receivers. Most receivers report these features using the NMEA 0183 protocol. Therefore, data acquisition techniques only require a standard RS232 connection.

GPS satellites can also be used as remote monitoring sensors to collect system performance data for different elevation and azimuth angles. The principle feature value of a particular satellite is dependent on the satellite's elevation angle with respect to the receiver.

The principle feature value can be plotted and normalized to generate a model with one degree of freedom. Fig. 9 illustrates the fitted model, represented by a Gaussian distribution, used to normalize the principle feature. Additionally, the effects of low elevation noise, such as the multi-path effect, are minimal for elevation angles greater than 30°.

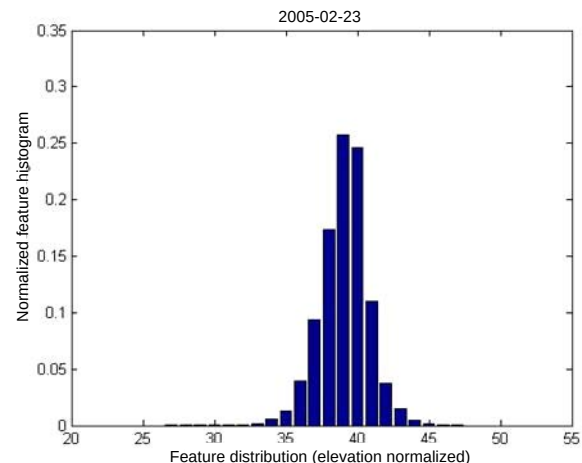


Fig. 9. Histogram of normalized feature data (Data measured on 2-23-05).

ACCELERATED FAILURE TESTING

Accelerated failure testing validated the derived diagnostic feature set. Accelerated failure testing is the process of determining the reliability of an electrical system over a short period by accelerating environmental conditions as described by the MIL-STD-810 specification [5]. Accelerated failure tests were conducted by placing a GPS receiver (Garmin GPS 15L-W), or the Device Under Test (DUT), into an environmental chamber exposing the DUT to thermal cycling. During the test, the DUT received a constant reference signal from a GPS satellite simulator located approximately six feet away. A laptop monitored the features using a RS-232 connection. Thermal cycling halted every 100 cycles to record 24 hours of live constellation data. The cycle time between data collections lasted 40 minutes. Fig. 10 shows the setup for the accelerated failure test.

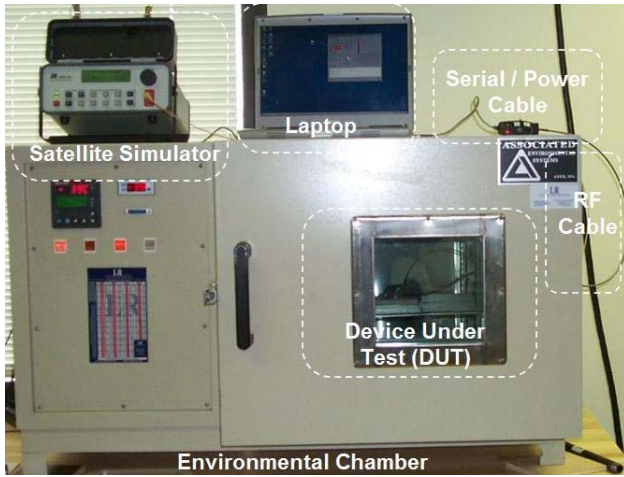


Fig. 10. Accelerated failure test setup.

EXPERIMENTAL RESULTS

Two Garmin GPS receivers were tested to failure. The first GPS receiver (S/N 81417589) failed on April 14th 2005. According to the test logs, the environmental chamber was set to cycle between -40°C and 95°C with a total cycling time of 40 minutes per cycle (Fig. 11). The principle feature offset was calculated with live constellation data. A solution failure occurred when the offset dropped below 30dB. Therefore, the last data point was extrapolated using the GPS Satellite Simulator. The second GPS receiver (S/N 81417585) failed on May 31th 2005. The environmental chamber was set to cycle between -40°C and 110°C with a cycling time of 40 minutes. Fig. 12 shows the results of the experiment. The first five data points followed the exponential trend given in Equation 1. The amount of thermal cycling applied to the GPS receiver after the 5th measurement was determined by using the

best fit line in Fig. 12. 1000 minutes (or 25 cycles) of additional accelerated failure testing was necessary to achieve the targeted reduction in the feature offset value. The GPS receiver was then subjected to an additional 1000 minutes of thermal cycling immediately proceeded by recording 24 hours of live constellation data. Further degradation in the principle feature value (PFV) offset resulted.

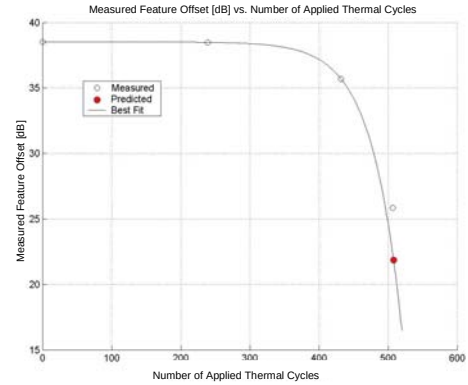


Fig. 11. Measured PFV offset vs. Number of Applied Thermal Cycles for a Garmin GPS receiver (S/N 81417589).

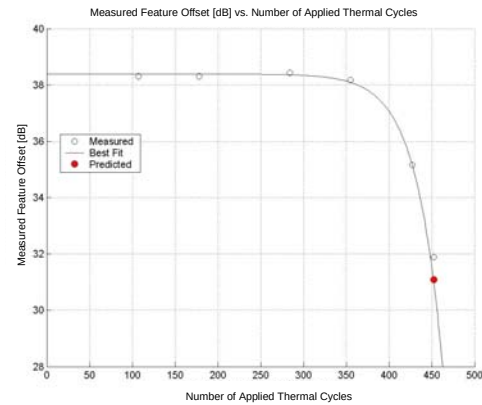


Fig. 12. Measured PFV offset vs. Number of Applied Thermal Cycles for a Garmin GPS receiver (S/N 81417585).

The equation below calculated the predicted value of PFV offset.

$$PFV = A + B \exp(\lambda N) \quad (1)$$

The best-fit parameters for each test are provided in Table 2 where A , B , and λ are experimental fitting parameters and N represents the number of applied thermal cycles.

Table 2. Experimental Fitting Parameters

Device Under Test	Fitting Parameters (Eq. 1)
GPS Receiver (S/N 81417589)	$A = 38.53[\text{dB}]$ $B = -2.927\text{e-}004 [\text{dB}]$ $\lambda = 2.1251\text{e-}002$
GPS Receiver (S/N 81417585)	$A = 38.39 [\text{dB}]$ $B = -3.423\text{e-}006 [\text{dB}]$ $\lambda = 3.2197\text{e-}002$

ELECTRONIC PHM DEVELOPMENT

Feature-based diagnostics and prognostics can be implemented for electronic systems by identifying key prognostic features that correlate with failure progression. Obtained features can be tracked and trended over the system's life and compared with the model-based useful-life-remaining estimates to provide collaborative evidence of a degrading or failing condition. A feature-driven artificial intelligence-based approach can implement such a PHM system. With examples of good, bad, and unknown feature sets, classifiers can be developed using an array of techniques from straightforward statistical methods to artificial intelligence methods such as neural networks and fuzzy logic systems. For a prognostics implementation, the automated reasoning algorithm can be trained on evidence-based features that progress through a failure. In such cases, the probability of failure, as defined by some measure of the "ground truth", trains the predictive algorithm based on the input features and desired output prediction. In the case of a neural network, the network automatically adjusts its weights and thresholds based on the relationships between the probability of failure curve and the correlated feature.

The theoretical concepts and experimental results discussed in this paper combine to create a real-time PHM system for a Garmin GPS receiver (model: GPS 15L-W). The real-time health monitoring system utilized a MATLAB GUI as part of the experimental set-up. The system used data from the accelerated failure tests to display the progression of component degradation. Fig. 13 shows the PHM results from a healthy Garmin GPS receiver and its associated health index. Fig. 14 shows the PHM results from a degraded Garmin GPS receiver and its associated health index.

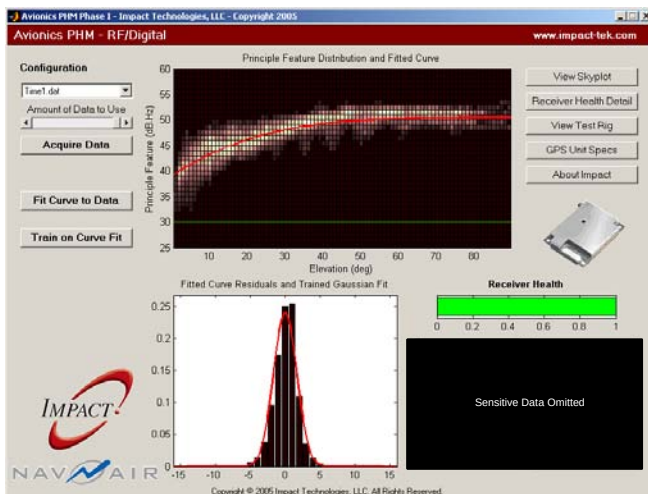


Fig. 13. Experimental GUI of healthy Garmin GPS receiver.

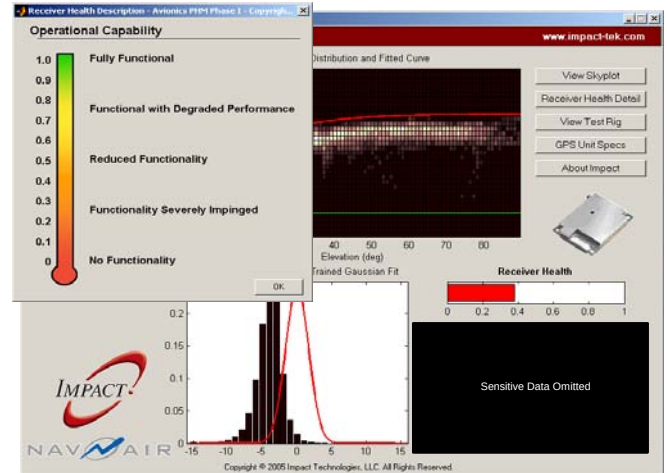


Fig. 14. Experimental GUI of degraded Garmin GPS receiver.

Utilizing sound engineering principles and building on diligent study of physical failure mechanisms, the developed electronic Prognostic Health Management (PHM) technology leverages existing circuit operational data as a basis for prognostic feature extraction and provides a high-confidence component health index. This index reflects the component's current operating condition and establishes the foundation for a prediction of remaining useful life.

Conclusion

The authors have identified four major electronic equipment classes used in avionic systems. The team examined major characteristics of multiple failure types and identified techniques useful for monitoring and predicting failures. A test article, chosen for its relevance to a large class of electronic failures was identified. The selection of GPS circuits for testing permits a substitution of economical test articles for destructive testing and data collection. The availability of an existing data stream permits monitoring and implementation of prognostic algorithms without additional sensors, an important aspect of the demonstrated technique. Software was developed following the NMEA 0183 protocol to interface a GPS Receiver required to perform the accelerated failure tests outlined in this report. The extracted signals investigated during the accelerated failure test provided a sound basis for feature extraction and statistical analysis.

The utilization of all of these sources of information has led to the development of a sophisticated algorithm (no additional sensors or circuit modifications required) that can make assessments and predictions of the remaining useful life of a GPS receiver for use in automated PHM systems.

Specifically, the technique, utilizing the existing GPS data (NMEA 0183 protocol), enables the following:

- No external circuit requirements
- No circuit or system alterations
- Data acquisition using low bandwidth connection.
- No external sensor requirements
- Identification and verification of features as traceable indicators of damage accumulation
- Feature extraction using the 24 active satellites of the GPS constellation.

This technique will extend to other RF electronic applications where digital data is readily available during the normal operation of the device. Software defined radios and radar applications are two examples.

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