SPECTRAL ANALYSIS FOR SPACECRAFT ANALOG TELEMETRY BEHAVIOR

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Failure Analysis

Spectral analysis decomposes a signal into its frequency components. Engineers can use spectral analysis to decompose Satellite and spacecraft telemetry behavior from space to provide a new tool to advance space vehicle reliability. The same tools used by RF and digital signal design engineers for identify signal integrity offers new understanding for telemetry behavior from space. Analysis illustrates the harmonic properties of telemetry behavior as a function of time, amplitude, frequency and phase. Expanding spectral analysis to satellites and spacecraft illustrates their fundamental harmonic properties. This information can be used to improve vehicle reliability and define vehicle and ground station telemetry system design performance parameters and reduce risk of catastrophic satellite and spacecraft failure.

Introduction

Man has been launching satellites and spacecraft since 1957 when the Soviet Union successfully launched the first of several Sputnik satellites in low-earth orbit which used a dual frequency telemetry system. Space vehicle equipment telemetry originating in space has been believed too complex and too varied in its behavior to quantify. However, after characterizing telemetry behavior on the Boeing/Air Force Global Positioning System in-orbit satellites, many properties were discovered that are usable across all satellites and spacecraft.

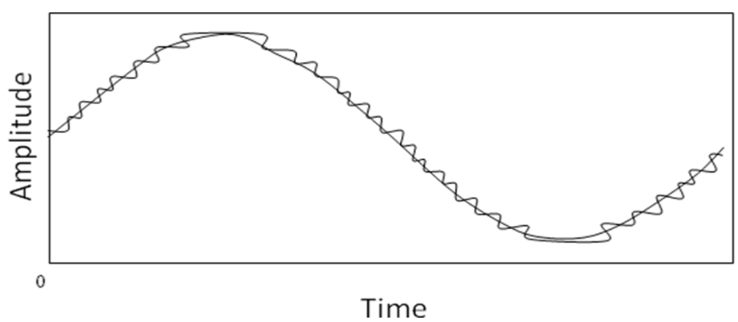

FIGURE 1 COMPARISON BETWEEN AN ORIGINAL ANALOG SIGNAL AND ITS RECONSTRUCTED ANALOG SIGNAL

Figure 1 illustrates an original analog signal and its reconstituted characteristics accomplished by a telemetry system. Today's long life communications satellites may use up to 5 for 1 redundancy to meet a 20 year design life. Satellite and launch vehicle reliability is around 25% infant mortality failure rate. Believing that there is no solution to the infant mortality problem for satellites and launch vehicle customers use commercial insurance companies to reduce risk of failures causing impact on financial assets and income. Understanding satellite equipment telemetry behavior can be crucial to the success of many business ventures that use satellites to earn income.

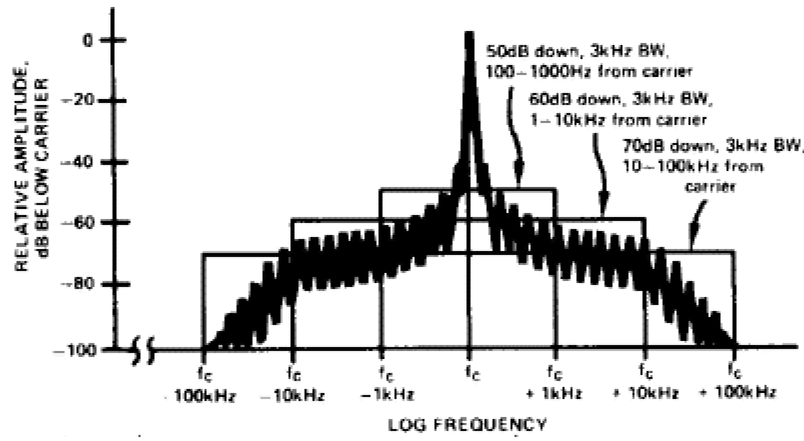

FIGURE 2 POWER SPECTRAL DENSITY (PSD) FOR AN RF SIGNAL

Spectral analysis is the decomposition of time-series electrical signals into its frequency and phase components. Spectral analysis is used in many applications to understand the electrical signal properties.

Figure 1 illustrates telemetry as reconstructed time-series analog signal, quantifiable using its amplitude, frequency and phase just as other electrical signals can be and the use mathematics developed for signal analysis and orbital mechanics. Space engineers remain unaware of the intelligence in telemetry signal behavior, usually referred to as systemic noise.

Telemetry has been for many decades, overhead, a cost of doing business, and not fully leveraged to reduce risk to satellites and astronauts. With 50 years of building and launching experience, there seems no way to improve vehicle reliably and cost effective balancing cost and risk.

[1]Telemetry is the source of information necessary to increase space vehicle reliability but has an industry reputation as being expensive, complex, unnecessary and unreliable, minimizing its use. Telemetry science makes telemetry behavior understandable, reliable, quantifiable and key to space program success, and can be used to justify the cost of expanding its use to all equipment. Using RF and digital electrical signal spectral analysis, the harmonic influences can be understood and leveraged as another tool for engineers to minimize risk of catastrophic spacecraft equipment failure.

VIRTUAL TELEMETRY ELECTRONIC SIGNAL (VTES)

Telemetry originating from satellites in space, exhibit unique behavior similar to electrical signals. Until know, these properties have been relatively undiscovered. Engineers responsible for the operations and maintenance of spacecraft and satellites use telemetry to determine the spacecraft Bus equipment and payload status and operational performance. Telemetry is often recorded and made available in large quantities to engineers for evaluation. As a consequence, engineers have developed many tools to automate the evaluation of large quantities of telemetry.

Telemetry from satellites and spacecraft is a reconstruction of an analog signal. For satellites in a circular orbit, without external influences, a satellite's earth orbit is a perfect circle or ellipse, however, the Earth's non-uniformity and influences from the sun, all other moons and planets and other influences causes both in-track and out-of-track effects. Starting with a perfect orbit circular shape, and no short or long term influences, the behavior that a typical analog telemetry measurement creates from orbit is that of a sinusoidal signal. This (virtual) telemetry electrical signal (VTES) can be treated as an electrical signal with all the same properties.

To quantify the behavior of electrical and RF signals, harmonic and Fourier analysis are used. [2]Harmonic and Fourier analysis is the decomposition of a function in terms of a sum of sinusoidal basis functions that can be recombined to obtain an approximation to the original function.

Every analog or digital signal can be written as a (infinite) sum of sine and cosine functions of different frequencies; this is the basic idea of Fourier analysis, where trigonometric series are used to solve a variety of boundary-value problems using partial differential equations.

To convert from orbit position to harmonic time series data (telemetry), trigonometric functions are used. The sine of a real number, t is given by the y-coordinate (height) of the point P in the following diagram, in which t is the distance of the arc shown: The sin of a real number t is given by the y-coordinate (height) of the point P in the following diagram, in which t is the distance of the arc shown. Figure 2 illustrates circular or elliptical motion converted to times series data.

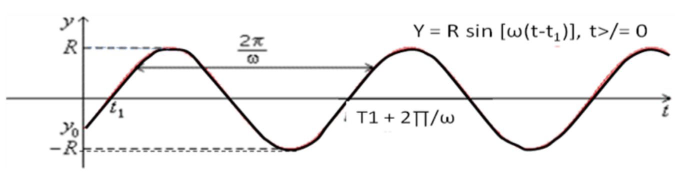

FIGURE 3 HARMONIC FUNCTION

From the relationship for time and amplitude varying electrical signals, Fourier analysis uses:

$$\text{For: } x(t) = A\sin(\omega t + \varphi)$$
$$\int x(t) = f_{\omega}(\omega)$$
$$\int f_{\omega(}(\omega) = f_{\varphi}(\varphi)$$

Fourier's representation of functions as a superposition of sine's and cosines has become ubiquitous for both the analytic and numerical solution of differential equations and for the analysis and treatment of communication signals. Figure 3 represents time series and magnitude data, frequency and amplitude components and phase magnitude components for an analog measurement.

Fourier analysis changes time series data to frequency and phase data. Frequency data shows when time series data changes which aids in identifying important values within the original time series data. Because orbiting satellites repeat their behavior every orbit, telemetry measurements repeat their behavior every orbit period allowing many generalizations. For an electrical signal, modulating the amplitude provides a means of adding information. For telemetry behavior, modulating the amplitude of the VTES occurs from external influences such as the changing sun-to-orbit plane angle (β). For an electrical signal, when the carrier is modulated, its amplitude goes above and below its unmodulated amplitude. The maximum percentage modulation possible is 100%. Going above this causes distortion. Distortion is bad because our equipment technology cannot accurately recover information accurately from an intentionally distorted signal.

Some signals which are intentionally distorted can be recovered by knowing how the originally signal was distorted. Figure 4 illustrates modulated and unmodulated electrical signal.

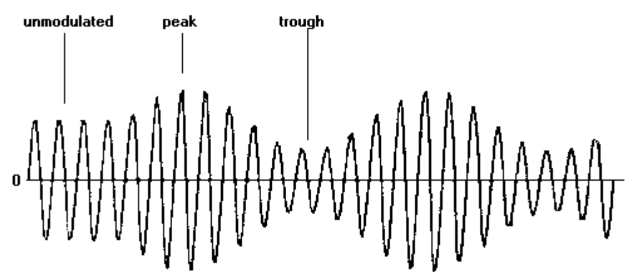

FIGURE 4 AMPLITUDE UNMODULATED PORTION AND MODULATED SIGNAL

[3]Modulation is a process in which a modulator changes some attribute of a higher frequency carrier signal proportional to a lower frequency message signal. A change in the message signal will produce a corresponding change in the amplitude, frequency, or phase of the carrier or a change in a combination of these. A signal transmitter can then send this carrier signal through the communication medium more efficiently than the message signal alone. Finally, a receiver will demodulate the signal, recovering the original message.

In amplitude modulation (AM), the amplitude of the carrier changes based on the amplitude of the message.

The message signal rides on top of the carrier as the amplitudes of both vary with time. The frequency of the carrier, however, is much higher than the frequency of the message. This carrier frequency is the center of the 'channel,' or frequency allocation of this signal. Frequency allocations vary depending on the medium of transmission. [4]For broadcast transmissions, where signals are sent through the air, the government regulates frequency allocation. If the RF signal is transmitted over wire, such as in cable television, there is more freedom in the choice of carrier.

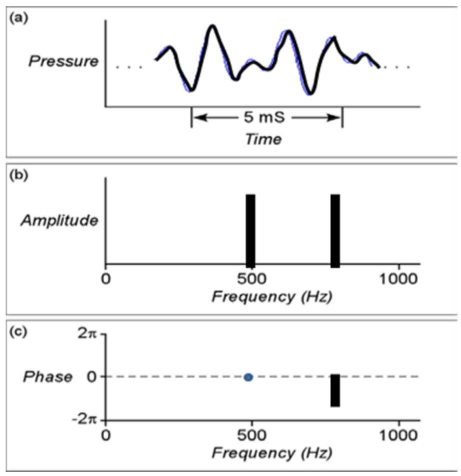

FIGURE 5 ANALOG ELECTRONIC MEASUREMENT SINUSOIDAL BEHAVIOR AND ITS FREQUENCY AND PHASE SPECTRUM

BASEBAND, PASSBAND SIGNALS AND AMPLITUDE MODULATION

Due to their low frequency content, the information signals have a spectrum such as that in the Figure 6 below. There are a low frequency components and the one-sided spectrum is located near the zero frequency.

The hypothetical signal in Figure 6 has four sinusoids are fairly close to 0 frequency. The frequency range of this signal extends from zero to a maximum frequency of f_m. We say that this signal has a bandwidth of f_m. In the time domain, this 4 frequency component signal may look as shown in Figure 6.

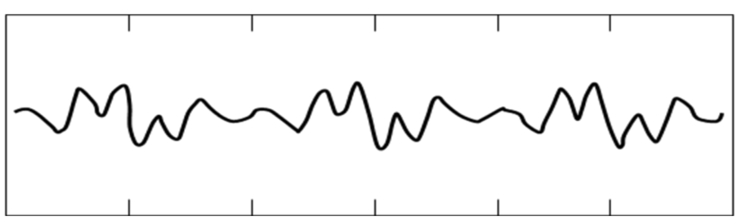

FIGURE 6 TIME DOMAIN LOW FREQUENCY STEADY-STATE INFORMATION SIGNAL WITH PHASE MODULATION

FIGURE 7 THE FREQUENCY SPECTRUM OF FIGURE 5

HARMONIC INFLUENCES OF SATELLITE TELEMETRY

Harmonic influences of satellite VTES include (1): orbit plane drift rate caused by solar, lunar and planetary gravity forces changing sun-to-orbit plane angles (β) and (2): the earth's solar constant (ς) which changes ~5% peak-to-peak per year.

[5]The beta (β) angle is the angle between the satellite orbit plane and sun vector. Beta is fixed for sun-synchronous orbits and variable for asynchronous orbit planes. Beta can vary from 0^o, when the sun is in the orbit plane and 90_o when the orbit plane is orthogonal to the orbit plane. For low earth circular orbits, orbit planes, β changes very quickly.

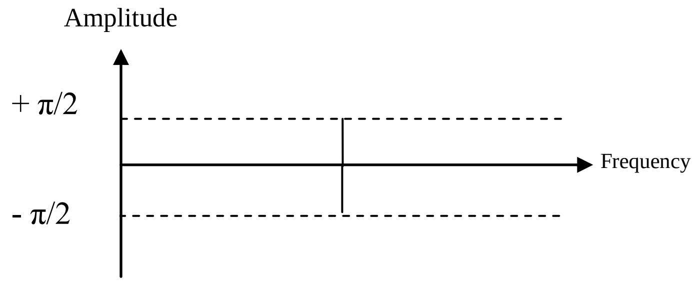

FIGURE 8 PHASE SPECTRUM FOR FIGURE 11

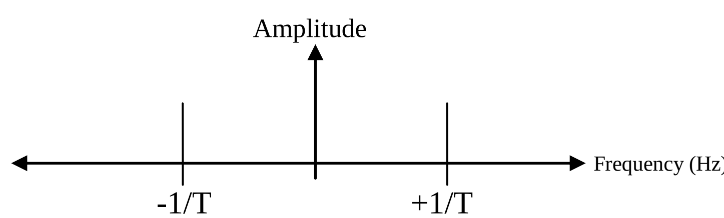

FIGURE 9 FREQUENCY SPECTRUM FOR TELEMETRY

NON-HARMONIC INFLUENCES

Non-harmonic influences include the location of the telemetry measurement, either internally to equipment or located in an area or region inside or outside the vehicle. Analog measurements in different quadrants will behave within well definable phase relationships based on the difference in time from exposure to solar input plus or minus a delay. The magnitude of the peak and minimum values may also differ.

Another non-harmonic influence on telemetry behavior is the change in spacecraft's thermal blanket absorptivity/emissivity (α). Satellite and spacecraft thermal blanket ability to provide insulation and protection changes in a predictable way. Thermal blankets shield the equipment from the damaging effects of solar radiation. [6]Without the protection of earth's atmosphere, spacecraft are exposed to the full energy spectrum of the sun which degrades everything it radiates. When the solar radiation isn't present, the equipment is exposed to the extreme low temperatures of space. The thermal blankets outer layer is exposed to a 120^{o}C degree change from sun to shade every orbit. To provide insulation, the thermal blanket material used is many layers of aluminum with an outer Teflon skin. It protects the onboard instruments against extreme temperature swings even though the blanket is incredibly thin and light-weight, measuring less than one-tenth of an inch thick.

ELLIPTICAL AND CIRCULAR ORBITS

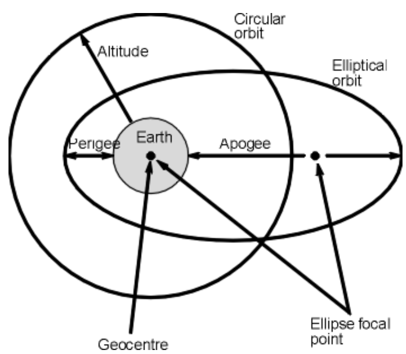

FIGURE 10 FIGURE CIRCULAR AND ELLIPTICAL ORBITS SHAPES

For a satellite in a circular orbit, its speed is constant and its altitude from the earth is fixed. A satellite in an elliptical orbit, velocity changes with its position around the orbit and its altitude changes symmetrically. In an elliptical orbit, the earth is located at one focus. The satellite's orbit will have a perigee and an apogee. [7]A satellite in an elliptical orbit exhibits different virtual telemetry signal behavior than from a circular orbit. In an elliptical orbit the velocity is higher during perigee than during apogee and the time that a satellite is close to the earth is far shorter than the time it is far away from the earth. While a satellite is approaching perigee its velocity increases. When a satellite is moving away from the earth after passing through perigee, its velocity slows until it reached apogee and then begins to increase again after it passes apogee and is on its way back to perigee.

The virtual telemetry electronic signal for a satellite in an elliptical orbit has a fixed frequency and phase but is not symmetric in amplitude. For satellites in elliptical orbits, the earth can be much closer at perigee than for circular orbiting satellites and may influence the behavior of many measurements.

Because of a significant perigee, the unbalanced gravitational forces for an elliptical orbit during perigee passes can cause its Ω-dot to be very high. With continuously varying altitude, higher Ω-dot, the eclipse periods may not be as symmetrical as for circular orbits. Their duration of eclipses and their frequency of eclipses are more difficult to envision.

The virtual telemetry electronic signal for an elliptical orbit can be made from the positive amplitude sinusoidal function and a negative amplitude sinusoidal function. The point at which the virtual telemetry electronic signal is 0-amplitude is equal to the ratio of the semi-minor axis to the semi-major axis of the ellipse the orbital period.

INFLUENCES FROM SATELLITE DESIGN PARAMETERS ON VIRTUAL TELEMETRY ELECTRONIC SIGNAL BEHAVIOR

Satellites and spacecraft vary in many design parameters. The different design parameters can influence telemetry measurement behavior. Vehicle attitude control approaches often used include gravity-gradient, spin-stabilized and 3 axis stabilized. Gravity-gradient satellites will keep their orientation towards the earth based on the very small change in the force of gravity over a short distance.

Figure 10 illustrates the long term analog telemetry measurement behavior from a measurement located inside a satellite with a 12 hour orbit for a 30 day period. Because it is identical in behavior to an analog signal, the analysis used to understand the properties of an electrical signal, e.g. modulation, demodulation, S/N, etc. can be used. Due to the large amount of telemetry available for analyzing, only the minimum, average and maximum values are used in Figure 10. A satellites regular equipment cycling is observable in its frequency and phase analysis includes:

- Equipment thermal heater cycling every 3 hours for minimum temperature control (9.25×10^{-5} Hz)
- Equipment thermal heater cycling every 4 hours for minimum temperature control (6.9×10^{-5} Hz)
- Rate gyro cycling weekly to assure its availability for loss of earth-lock recovery activities (1.65×10^{-7} Hz)
- TT&C subsystem actvation every 6 hours during regular telemetry collection periods (4.6×10^{-5} Hz)
- Battery reconditioning every 5 months (7.7×10^{-8} Hz)
- Eclipse season operations every 5 months for a 30 day period (6.4×10^{-8} Hz)
- An increase in the frequency to 1/hour for TT&C contacts at 0^o sun-to-orbit plane angle to determine thermal blanket emmissivity/absorptivity rate change (2.7×10^{-4})
- Minimum sun-to-orbit plane angle every 6 months (6.4×10^{-8} Hz)

- Maximium sun-to-orbit (β) plane angle every 6 months (6.4×10^{-8} Hz)

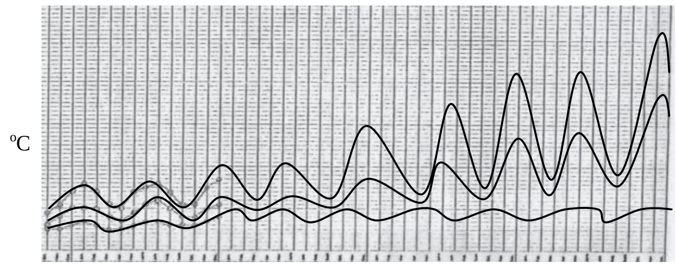

FIGURE 10 MINIMUM, AVERAGE AND MAXIMUM TELEMETRY VALUES FOR THE 4 YEAR LIFE OF GPS SATELLITE IN 12 HOUR ORBIT WITH 2 ORBITS PER DAY WITHOUT EQUIPMENT CYCLING

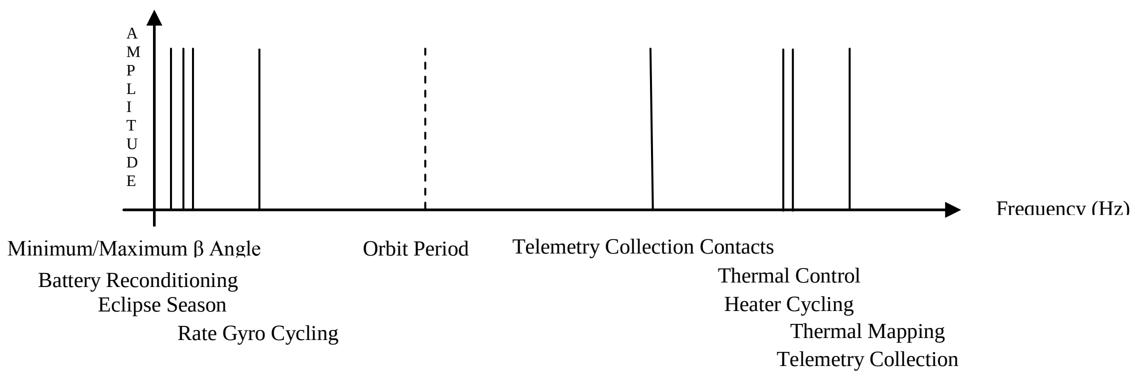

FIGURE 11 FREQUENCY SPECTRUM (POSITVE FREQUENCIES) FOR BOEING GPS BLOCK I SATELLITE

Figure 11 illustrates the frequency spectrum for the harmonic behavior in figure 10. Telemetry measurements include engineering data such as voltage, current, temperature, rpm's, attitude errors, attitude motion rates, frequency, etc. Satellite's, in-orbit or in factory test telemetry behavior mimic properties of an electromagnetic signal and are referred to as virtual telemetry electrical signal (VTES). The mathematics and principals used to understand RF and digital communications signals are applicable to some telemetry behavior.

CONCLUSION

Fourier analysis and spectral analysis can be used to determine satellite equipment telemetry behavior quality from space. Sharing many properties as electrical signals, telemetry behavior from satellites can be another tool to quantify satellite and spacecraft equipment integrity. The intelligence added using harmonic signals to electrical and RF signals are similar to the harmonic influences that effect normal telemetry behavior and can be used to define equipment behavior. This analysis can be used by engineers to decrease risk for spacecraft owners and operators.

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