USING ORACOL® FOR PREDICTING LONG-TERM TELEMETRY BEHAVIOR FOR EARTH AND LUNAR ORBITING AND INTERPLANETARY SPACECRAFT

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Failure Analysis

ABSTRACT

Providing normal telemetry behavior predictions prior to and post launch will help to stop surprise catastrophic satellite and spacecraft equipment failures. In-orbit spacecraft fail from surprise equipment failures that can result from not having normal telemetry behavior available for comparison with actual behavior catching satellite engineers by surprise. Some surprise equipment failures lead to the total loss of the satellite or spacecraft. Some recovery actions from a surprise equipment failure increase spacecraft risk and involve decisions requiring a level of experience far beyond the responsible engineers.

KEY WORDS

Telemetry, Behavior, Analysis, Prediction, Predicting, Satellites, Spacecraft, Transducer, Measurements, Prognostics, Prognosis, Algorithm

INTRODUCTION

Satellite and spacecraft builders do not generate normal telemetry behavior predictions for the life of a spacecraft during test. Predicting accurately long-term satellite and spacecraft telemetry behavior generically came about as the result of the development of prognostic technology. Diagnostics allows the identification of equipment that has failed.

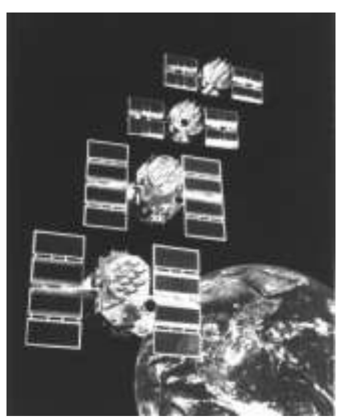

FIGURE 1 THE MANY BOEING/AIR FORCE GLOBAL POSITIONING SYSTEM BLOCKS I, II, IIA SATELLITES DESIGNED USING PROGNOSTIC TECHNOLOGY

[1]Prognostic technology is used for the identification of the information prognosticians use to predict equipment that is going to fail. In order to predict equipment failures, prediction of (unavailable) normal behavior was necessary. Prognostics was used on the first 12 Boeing/Air Force Global Positioning System (GPS) satellites to predict on-board atomic clock failures. The next 40 GPS satellites were designed based on the prognostic analysis completed on Block I GPS satellites.

Expected satellite and spacecraft analog telemetry behavior in a space environment is not generated during factory acceptance test, thus a-priori telemetry data is not available prior to or after launch for the environment. Telemetry simulators are available to validate telemetry processing and display software, validating the telemetry structure and the needed decommutation, algorithms for determining correct configuration and operating performance and data display for the hundreds of digital and analog telemetry measurements.

Spacecraft are launched into orbit without definitive analog telemetry behavior. Vehicle modeling tools used to design satellites and spacecraft are used to verify that the spacecraft environment will be well within equipment acceptance and qualification limits. Spacecraft engineers must use a “wait and see’ approach to quantify and qualify satellite and spacecraft in-space actual telemetry behavior waiting until the spacecraft has operated in space to decide what is “normal” behavior.

Having the information to decide immediately after launch what is normal analog telemetry behavior can reduce catastrophic loss due to infant mortality failures. Oracol® is a Windows-based telemetry behavior generation service that predicts normal, long-term telemetry behavior, available before launch, during spacecraft ground systems development, prior to launch. It uses known harmonic and non-harmonic influences to provide spacecraft engineers, the information to train and gain experience in normal satellite and spacecraft telemetry and develop analysis tools to evaluate all analog telemetry behavior and determine from initial orbit injection long term operating status of all on-board equipment.

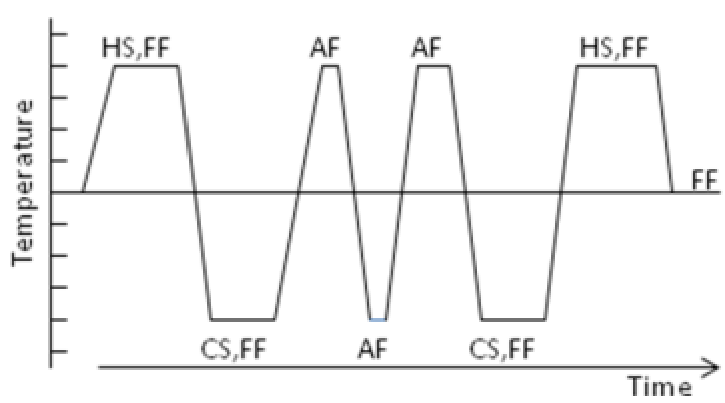

FIGURE 2 SPACECRAFT THERMAL VACUUM CHAMBER TEMPERATURE PROFILE DURING TEST

Spacecraft and launch vehicles suffer from a ~25%, 1st year infant mortality failure rate. Many infant mortality failures are from surprise failures that could have been identified early and managed to reduce risk of total failure by using telemetry behavior predictions for comparison between actual and predicted behavior. To stop a loss from a surprise equipment failure, engineers need to have normal telemetry behavior identified for diagnostic purposes to identify analog telemetry behavior indicative of a failure.

Spacecraft analog measurements are reconstructed analog electrical signals. Analog telemetry is added to satellites and spacecraft to provide engineers on Earth and on-board diagnostic tools information to determine equipment functional status, operating performance and configuration. [2]Factory thermal vacuum testing exposes spacecraft equipment and the vehicle to a highly limited set of environments, usually only hot and cold temperature extremes associated with acceptance values and other temperatures only briefly during temperature transitions. Figure 2 illustrates a thermal vacuum test temperature profile, which shows temperature history spacecraft are exposed to during thermal vacuum testing. The test starts and ends at room (ambient) temperature and includes hot starts (HS), cold starts (CS), full-functional tests (FF), and abbreviated functional tests (AF) are performed at temperature plateaus. When equipment fails or ambiguous data occurs, the thermal vacuum chamber is opened and equipment is repaired or replaced and the test is restarted.

Figure 3 illustrates telemetry, which is reconstructed analog signal. Telemetry is a reconstruction of an analog electrical signal. Because of the harmonic nature of orbits, telemetry from orbiting or interplanetary spacecraft results in the same properties as electrical and RF signals. Interplanetary spacecraft are traveling from one planet to another, the desired addition of energy to the trajectory, which are usually done using a rocket motor or ion thruster keep the spacecraft in an overall orbit trajectory. All interplanetary spacecraft remain are under the gravitation forces of the sun and planets and thus have an orbit trajectory with an apogee and a perigee for each change in energy. These orbit trajectories are either circular or elliptical which means that an analog measurement located anywhere on the spacecraft behavior will be similar to behavior from earth orbiting satellites.

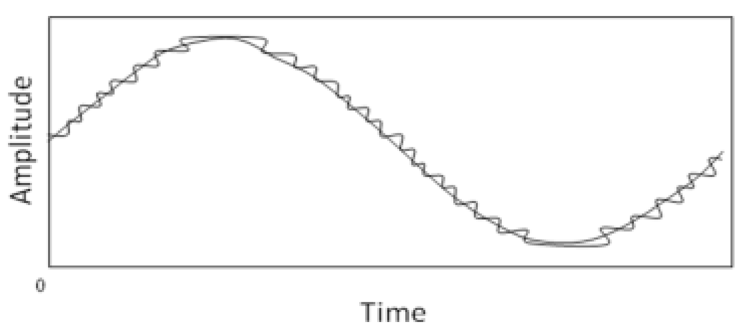

FIGURE 3 RECONSTRUCTION OF AN ANALOG SIGNAL FOR A CIRCULAR ORBIT

Using trigonometric functions, and Fourier analysis, telemetry behavior from spacecraft and satellites can be understood. For time series data from satellites and spacecraft, In-orbit/in-space spacecraft telemetry behavior is influenced by harmonic and non-harmonic influences and considered too complex to quantify. The values of telemetry measurements are controlled by the unique internal electrical and mechanical relationships for each circuit/unit the telemetry measurements are integrated. Coarse approximations are used from factory acceptance testing by using conditions as close as possible to the in-orbit conditions. Therefore, spacecraft engineers are not provided reliable a-prior information to know what to expect for on-board equipment telemetry behavior.

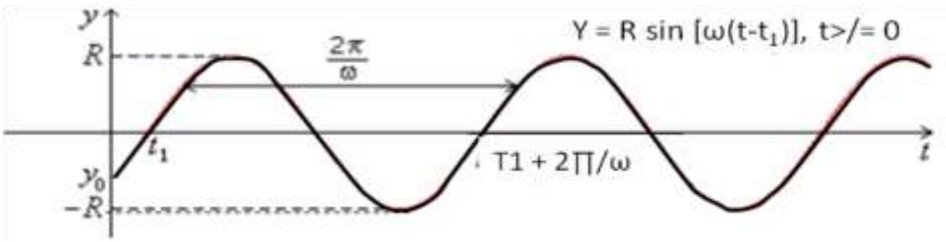

FIGURE 4 TIME SERIES DATA FROM CIRCULAR ORBIT

Due to cost and complexity, there is no attempt during factory test at modeling spacecraft sun angles and vehicle attitude orientations for providing telemetry behavior for spacecraft engineers to use as a reference to determine the operation reliability of the equipment. Only the extreme hot and cold environments are used. Pre-launch supplied telemetry behavior predictions for analog measurements can be updated later using actual in-orbit beginning-of-life values to increase long-term accuracy. Providing normal telemetry behavior predictions for satellite and spacecraft analog measurements for engineers usable during launch readiness activities can provide the foundation for spacecraft engineers to develop tools for to ensure spacecraft operations will be safe and reliable.

In-orbit spacecraft equipment will often fail while providing analog telemetry values well within normal operating behavior. [3]Spacecraft engineers learn the equipment is unreliable when it fails, causing high-risk activities that result in the complete failure of the spacecraft.
Current launch vehicle failure and in-orbit failure rate is 25% using acceptance testing. Obviously, the acceptance testing process is inadequate to identify infant mortality failures. To help avoid a catastrophic vehicle loss within the first year of in-orbit use, predictions for normal telemetry behavior can be used. This information provides a basis for determining if equipment is operating as expected.

Predicting equipment performance, functionality, reliability, size, mass, power needs are very common in aerospace industry. Predictions for important information are used throughout the launch vehicle/spacecraft/satellite design process including:

- Launch vehicle ascent trajectory
- Launch vehicle loads, vibrations and acoustic energy
- Launch vehicle attitude, stage separation, ignition times
- Upper stage separation time, velocity, orientation
- Spacecraft separation orientation

- Orbit tracking/orbital prediction ephemeris
- Launch vehicle and space vehicle mass
- Space vehicle electrical power needs
- Thermal blanket degradation rate
- Launch vehicle lift performance
- Upper stage mechanical and electrical interfaces
- Design life fuel/propellant usage
- Battery capacity long term degradation

ORACOL®

Oracol® is a Windows-based tool for providing long-term analog telemetry behavior for satellites and spacecraft in orbit. The results are intended to be a tool for spacecraft engineers to decrease risk of catastrophic vehicle and equipment failure.

Oracol® provides normal, in-orbit satellite telemetry measurement behavior predictions available months prior to and/or after launch. Oracol® is suitable for all spacecraft and satellites/orbits/altitudes/inclinations/attitude control /thermal control and electrical power configurations. Telemetry behavior predictions are not available before because no one believed it was possible to predict telemetry behavior.

Oracol® generates normal telemetry behavior for an unlimited duration of mission life. It is used by the satellite mission control team to define normal satellite equipment behavior, which is only observable through telemetry. Using normal telemetry behavior predictions, decreases risk of mission failure by identifying suspect equipment problems in advance. By studying telemetry prediction behavior, increases the depth of understanding of Satellite in-orbit behavior. It increases the technical ability of Mission Control personnel to quantify safe satellite equipment behavior.

Oracol® is used with telemetry prognostic technology for predicting satellite and launch vehicle equipment failures. Oracol® was created and used on the Boeing/Air Force Global Positioning System MEO satellites to identify satellite equipment that was going to fail.

Its benefits includes lowering the risk of mission failure by reduces the chances of surprise failures. Most in-orbit failures occur well within acceptance limits. Oracol® provides a warning that something has changed the expected behavior. It allows sufficient time for mission control team to respond/develop contingency procedure. It provides the information necessary for the mission control team to understand what should be occurring on a satellite. It can also be a training tool for mission control team to understand satellite equipment and subsystem electrical and mechanical interface relationships. Prior to launch, the mission control team has limited information regarding the long-term normal behavior of satellite from builder.

Oracol® uses harmonic and non-harmonic influences, which can be modeled to predict normal telemetry behavior for satellites and spacecraft for up to 30 years and more of mission life. Today's long life spacecraft have a greater chance of failing catastrophically from an equipment failure due the much larger number of piece-parts and the unavailability of high reliability piece-parts. Today's spacecraft are larger, more complex, less reliable and susceptible to single event upsets (SEU) and electrostatic discharge (ESD) failures due to the increased use of low voltage piece-parts.

Spacecraft engineers that develop software tools for evaluating telemetry quickly and accurately need a foundation to build on. Oracol® provides the information for pattern recognition software that can illustrate behavior not expected as well as information that should be looked at closer by engineers.

With spacecraft costs and complexity skyrocketing and reliability decreasing, increasing the competency of engineers that monitor and evaluate spacecraft telemetry becomes a more important activity to spacecraft owners and operators.

[4]Satellite and spacecraft telemetry behavior is a result of harmonic and non-harmonic influences. The influences cause changes that usually occur well within equipment acceptance limits. However, many equipment failures occur well within acceptance limits and are identifiable if normal telemetry behavior predictions are available. Understanding and quantifying telemetry behavior from spacecraft offers the owners and operators a tool to protect their expensive, but unreliable equipment.

Oracol® uses known influences and other controlling factors to predict normal telemetry behavior.

HARMONIC INFLUENCES ON ANALOG TELEMETRY BEHAVIOR

Harmonic influences include orbit plane drift rate caused by solar, lunar and planetary gravity forces, changing sun-to-orbit plane angles and the earth's solar constant which changes ~5% peak-to-peak per year.

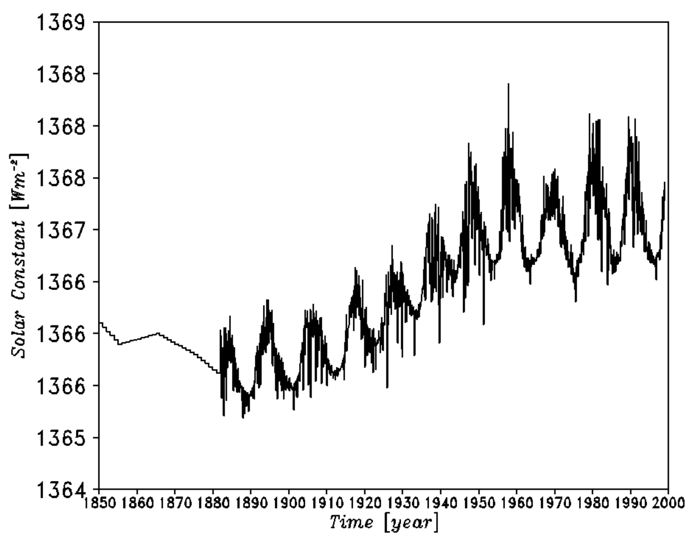

FIGURE 5 LONG TERM SOLAR OUTPUT REACHING THE EARTH

Figure 5 represents the output for the sun at the Earth from 1880 to 2000 indicating that there are both yearly and 11-year harmonic cycles. These cycles contribute to the peak and minimum temperatures for spacecraft.

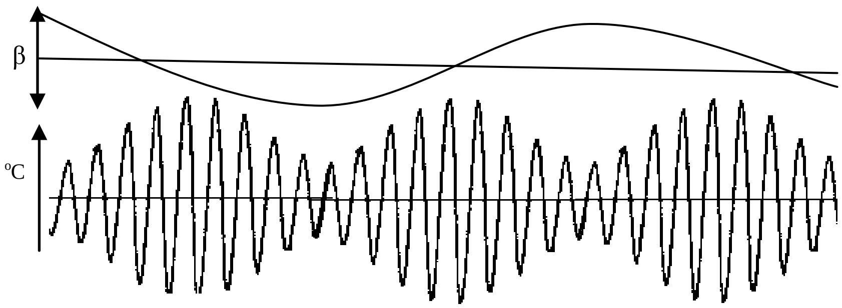

FIGURE 6 RESULTING SATELLITE TELEMETRY BEHAVIOR WITH CONTINUOUS CHANGING SUN-TO-ORBIT PLANE ANGLE

Figure 6 indicate the long term, peak-to-peak changes for a temperature measurement for a continuous changing, sun-to-orbit-plane (β) angle and the behavior of the minimum and maximum values for a measurement. [5]The peak-to-peak variation for a satellite temperature measurement is minimal when the β angle is at maximum and at maximum when the β angle is the lowest.

Figure 7 indicates the telemetry measurement behavior for a satellite with a fixed β angle and no degradation of the thermal blankets and thermal control subsystem

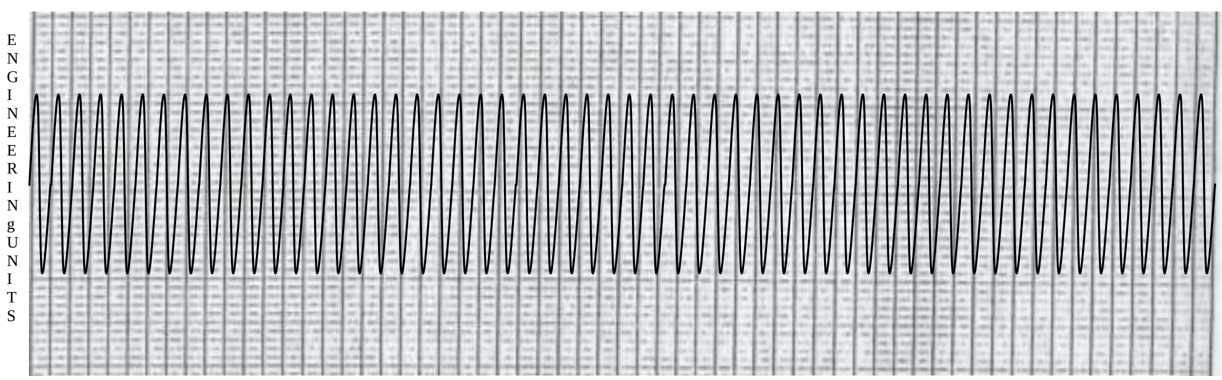

FIGURE 7 TELEMETRY BEHAVIOR FROM SATELLITE WITH A FIXED SUN-TO-ORBIT-PLANE ANGLE (β)

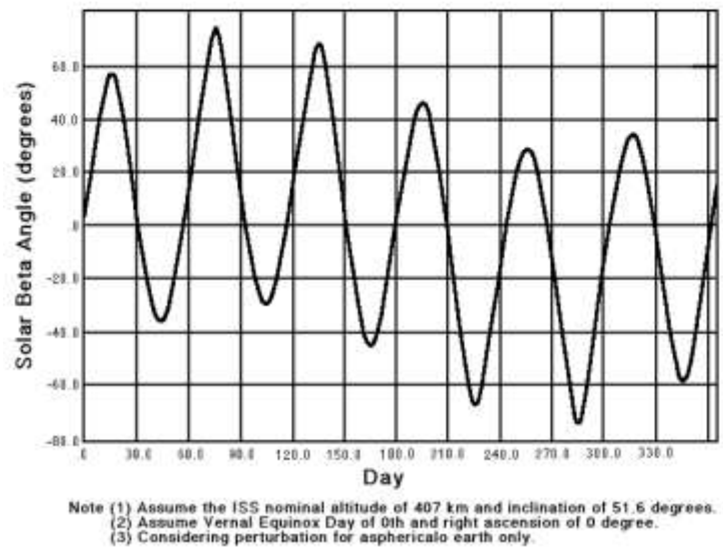

FIGURE 8 ANNUAL SPACE STATION SUN-TO-ORBIT PLANE β-ANGLE PREDICTION

Figure 8 illustrates the NASA Space Station β angle prediction for one year.

NON-HARMONIC INFLUENCES ON ANALOG TELEMETRY BEHAVIOR

[6]Non-harmonic influences include the location of the telemetry measurement, internally to equipment or located in an area or region. Analog measurements in different quadrants will behave within well definable phase relationships.

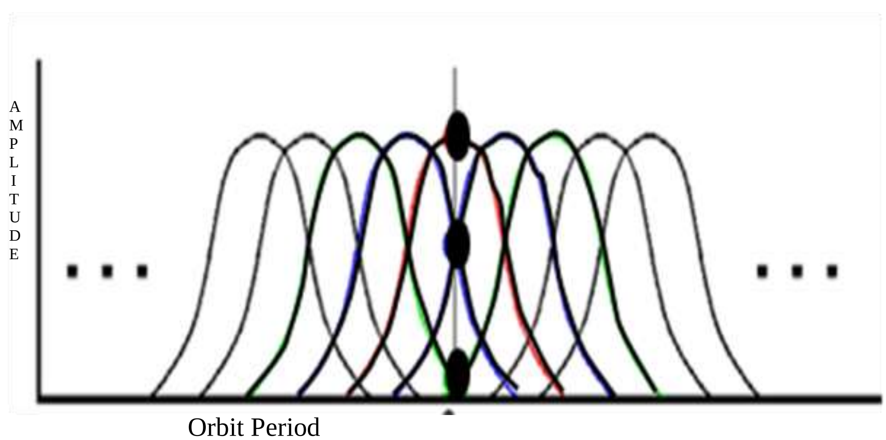

FIGURE 9 PHASE RELATIONSHIP BETWEEN SATELLITE/SPACECRAFT TEMPERATURE TELEMETRY MEASUREMENTS LOCATED IN DIFFERENT SATELLITE QUADRANTS

Another non-harmonic influence is the change in thermal blanket absorptivity/emissivity (α) and its long-term influence of telemetry behavior. This ratio is known as α. [7]Satellite and spacecraft thermal blanket α, increase over time in a predictable way.

To meet the needs of spacecraft engineers, Oracol® provides normal telemetry behavior predictions in several formats.

AVAILABLE FORMATS

A traditional format for time series information includes time vs. magnitude. This allows the identification of behavior in a time-based perspective. Figure 10 illustrates traditional time vs. magnitude information. Since telemetry is time-based data, engineers have used these representations to identify behavior that needs further research.

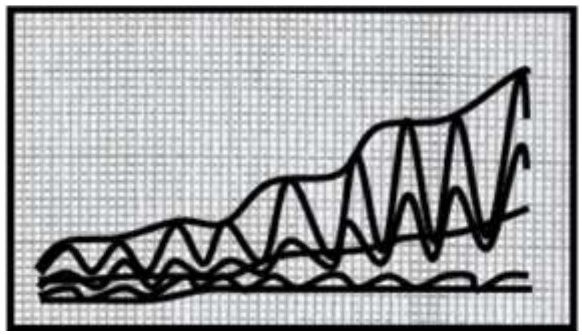

FIGURE10 FORMAT 1, 3-D TIME VS MAGNITUDE VS FREQUENCY: ORBIT, DAILY, WEEKLY, MONTHLY MINIMUM, AVERAGE, MXIMUM VALUES

Figure 11 illustrates 3-D, time vs. magnitude vs. frequency representations. These are used for enhanced analysis. Time vs. magnitude vs. frequency vs. phase representations allow the verification of normal behavior in all 4 dimensions understanding each harmonic contribution and identifying non-harmonic affects. Telemetry is time-based so analyzing its frequency and phase components helps to better quantify the results.

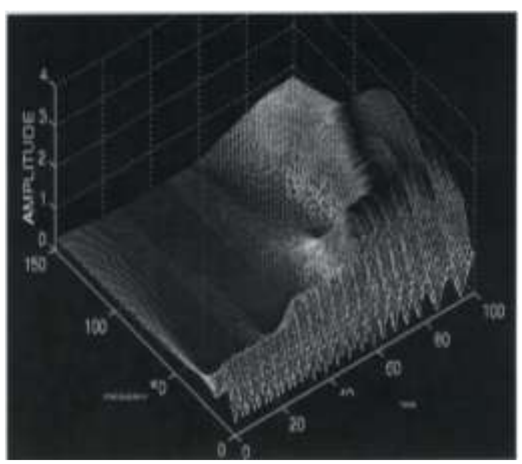

FIGURE 11 FORMATS 2, 3-D IMAGE OF LONG TERM IN-ORBIT NORMAL TIME, AMPLITUDE AND FREQUENCY TELEMETRY BEHAVIOR FROM ORACOL®

PATTERN RECOGNITION SOFTWARE

Oracol® normal telemetry behavior predictions results can be used with pattern recognition software to identify unexpected telemetry behavior.

CONCLUSION

Oracol® results provide the long-term telemetry behavior for spacecraft engineers to compare actual behavior with expected behavior to determine equipment status and performance. Oracol® results can stop surprise equipment failures by identifying normal behavior and comparing actual with expected behavior. Normal telemetry behavior predictions are available prior to launch and can be used to develop analysis tools for engineers to analyze spacecraft telemetry. Results based on actual behavior are available after orbit insertion. Oracol® predicts normal satellite and spacecraft long-term telemetry behavior by identifying harmonic and non-harmonic influences and their affect on telemetry behavior reducing risk to satellite and spacecraft owners and operators of catastrophic failures while increasing the technical level of spacecraft engineers.

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