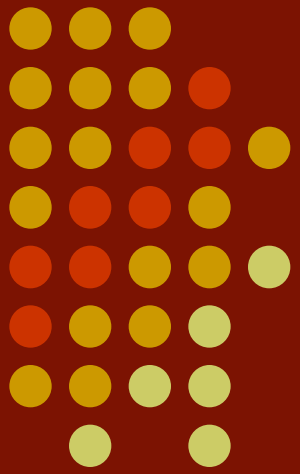
FA *Failure Analysis*

Engineering Services & Technology Licensing

Adapting Fourier Analysis for Generating Predictions of On-Orbit Spacecraft Equipment Telemetry Behavior



By

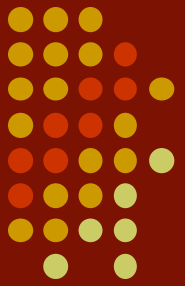
Len Losik Ph.D

Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior

- **Problem: Space Vehicle Equipment Fails On-Orbit Well Within Limits and Normal Operating Values**
  - Mission operations engineers do not have predictions of real-time behavior to compare with actual equipment telemetry behavior to identify accelerated aging
  - Many equipment failures occur well within normal operating conditions and then go outside
    - According to Aerospace Corporation, Air Force space missions have a 75% mission success after one year record from surprise equipment failures
    - According to Frost & Sullivan, the commercial space industry has a 75% mission success record as well from surprise equipment failures

$150M SUPERBIRD GEO Commercial Communications Satellite Failed

Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior



- **Surprise Earth, Lunar and Mars Satellite Equipment Failures Occur On-Orbit Increasing Risk to Mission**

Average Number of Mission Degrading Equipment Failures Occurring in Vehicle Level ATP After Equipment-Level ATP for 60 Air Force Satellite

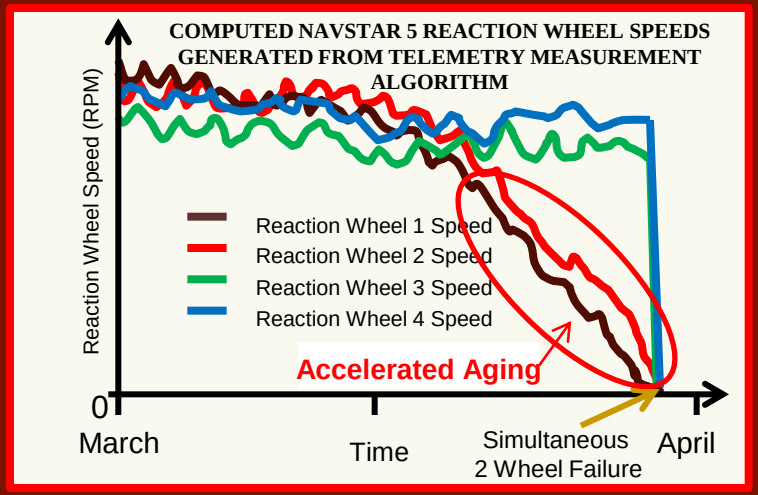
Program	No. of satellites tested	Test failures/satellite						No. of satellites flown	Flight failures/ satellite
		Acoustic	TC	Acoustic	TV	TC	Acoustic		Early flight (first 45 days)
E2	4	–	5.5	–	2.8	–	0.5	4	0.5
D1*	3	0.3	–	–	1.7	–	–	3	2.0
D2*	1	0	2.0	–	2.0	–	–	1	1.0
D3*	9	0.9	1.4	–	1.6	–	–	7	0.6
D4/D5*	2	0.5	1.5	–	0	–	–	1	0
B	16	0.6	–	–	1.2	–	–	11	0.6
G	4	1.0	–	–	3.8	–	–	3	2.0
F1	5	–	1.0	0.4	0.4	–	–	4	0.3
F2	3	–	4.3**	0.7	1.3	–	–	1	0
H1	2	0.5	–	–	5.5	–	–	2	1.0
H2a	1	2.0	–	–	2.0	6.0	–	1	1.0
H2b	2	0.5	–	–	3.0	9.0	–	2	0.5
C	8	1.1	–	–	3.0	–	–	7	0.4
Total: 60								Total: 47	
Weighted averages				4.0					0.7

*Spacecraft only.
**Pre-environmental functional part of TC.

Aerospace Corporation

Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior

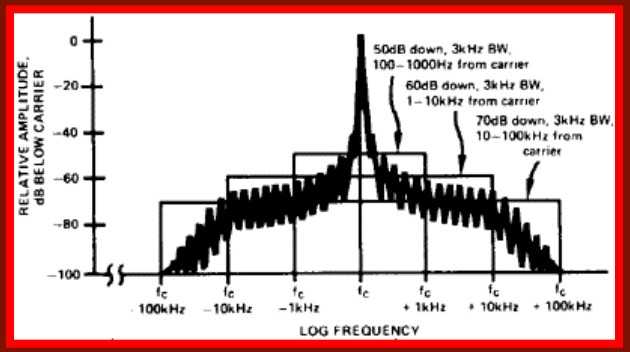
- **Prognostic Technology Illustrates the Presence of Accelerated Aging to Identify the Equipment that will Fail Prematurely with 100% Certainty**
  - Equipment failures do not have the Markov property (e.g. instantaneous & random)
  - Equipment failures are preceded by accelerated aging up to one year in advance allowing time to prevent and ***all*** equipment events to a positive conclusion



Accelerated Aging in GPS NAVSTAR 5 Reaction Wheel Telemetry from Dual Wheel Failure

Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior

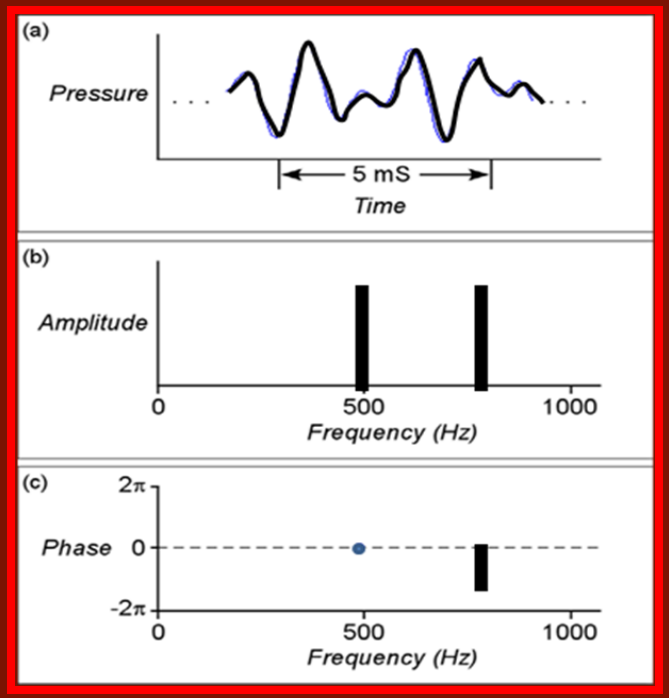
- **Solution: Use Fourier Analysis to Generate Equipment Telemetry Behavior for Comparison with Actual**
  - On-orbit satellites are at risk from engineers overlooking equipment that is failing with equipment telemetry behavior well within normal behavior (limits)
    - Equipment telemetry is well within normal operating values
  - Telemetry behavior predictions will allow engineers/software to compare actual equipment telemetry with expected equipment telemetry behavior



Power Spectral Density

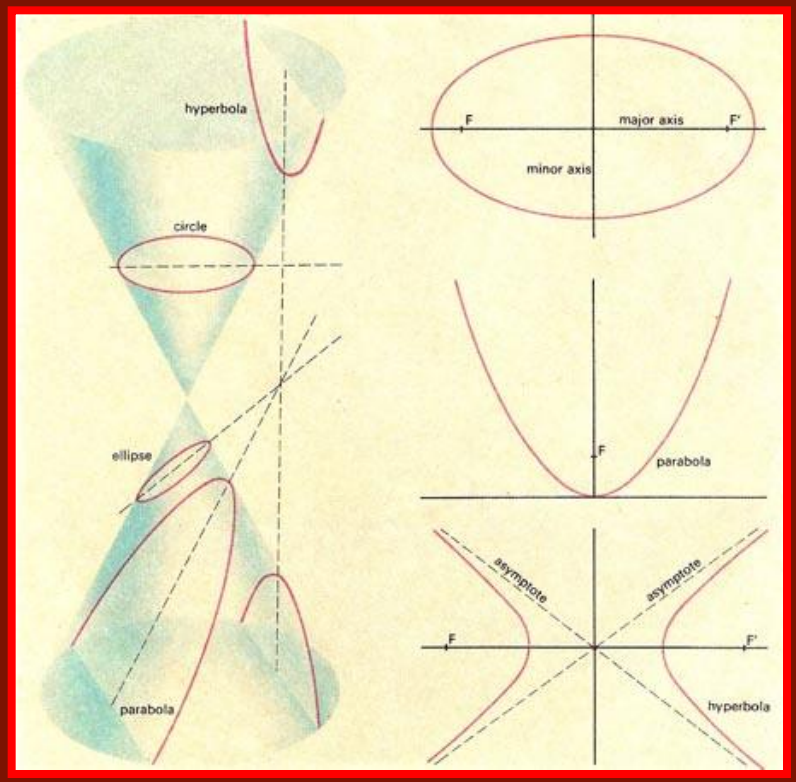
Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior

- **What is Fourier Analysis?**
  - The decomposition/substitution of a complex function into harmonic functions
    - Allows using harmonic analysis to solve unsolvable complex problems
    - The path of satellites and deep-space probes are harmonic due to sun/earth/moon $1/r^2$ gravitational forces they are in
    - Telemetry behavior can be defined with sine and cosine functions (harmonic functions)



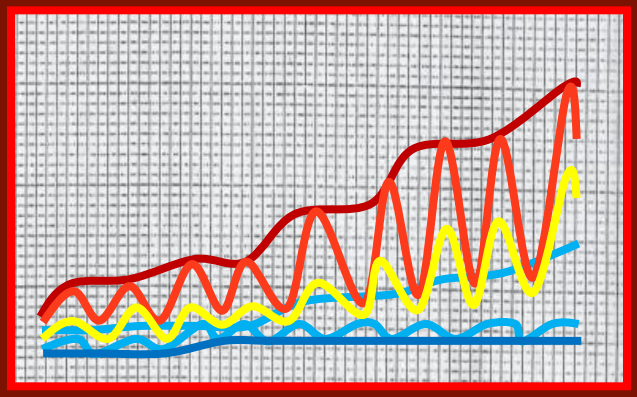
Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior

- **Normal Satellite Telemetry Behavior Mimics the Shapes of Conic Sections**
  - Satellite orbits and spacecraft trajectories are conic cross sections due to the gravitational fields of the sun, planets and moons on a body in the solar system
  - Satellites and spacecraft telemetry behavior exhibit the same properties of the conic section that best matches the orbit trajectory thus allowing the use of Fourier analysis
  - When telemetry behavior is different than expected , it may be from the presence of accelerated aging



Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior

- **Purpose of Using Fourier Analysis/Spectral Analysis**
  - To identify any accelerated aging that precedes equipment failures present in analog telemetry for increasing space vehicle safety
    - Pure telemetry behavior is 100% harmonic
    - Real telemetry behavior is not
      - External spacecraft influences
        - Harmonic /Non-harmonics
        - Polynomial
      - Internal source influences
        - Local equipment cycling

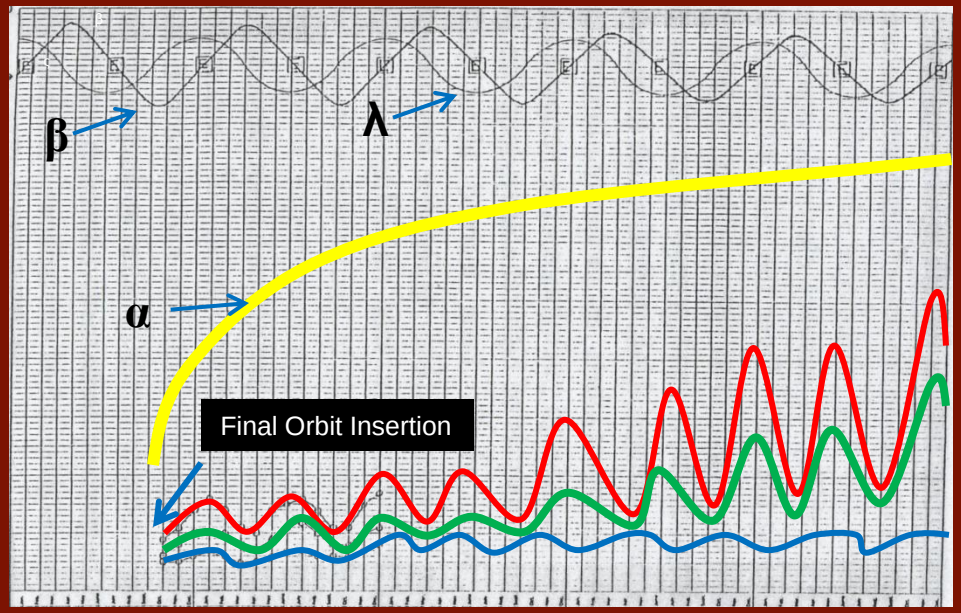


Real Telemetry Behavior

- Equipment telemetry that will fail prematurely exhibit noise that can be found using Fourier Analysis

Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior

- **Influences on Time Series Behavior Include Sinusoidal, Non Sinusoidal and Polynomial Influences**



°C

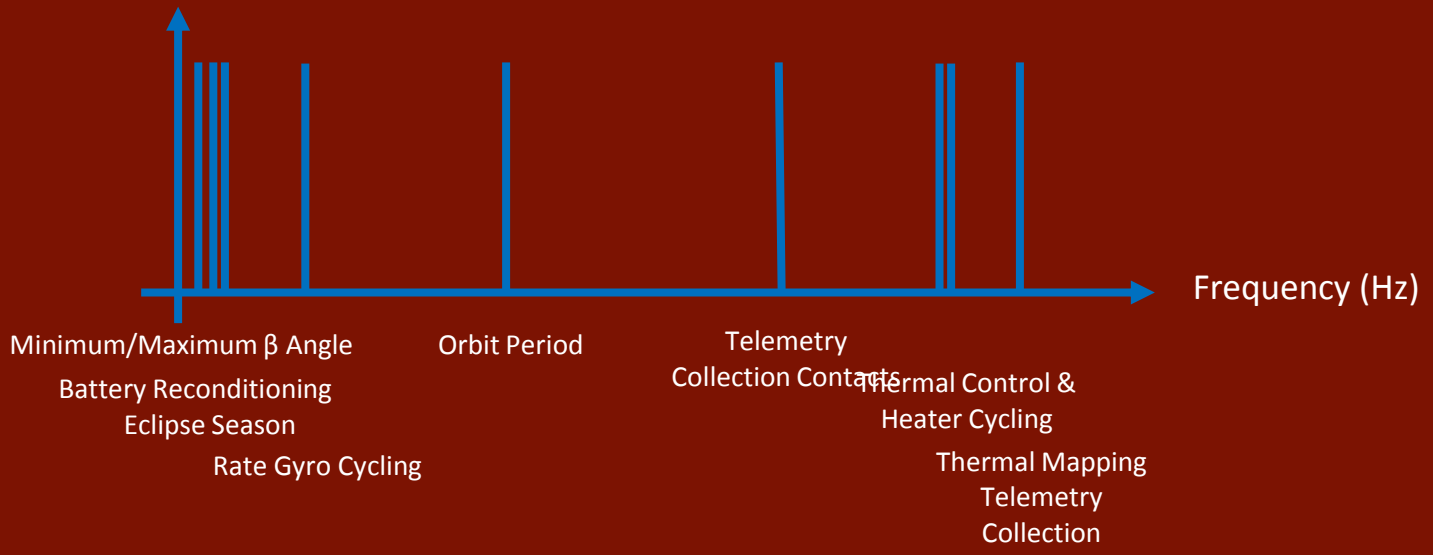
Telemetry Orbit
Minimum,
Average,
Maximum Telemetry Values

5 Years of GPS Satellite Time-Series Equipment Telemetry Behavior

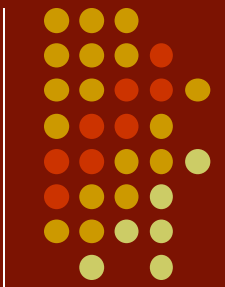
Includes influences from solar constant (γ), sun-to-orbit plane angle (β), solar eclipse, lunar eclipses, degradation of the thermal blankets (α)

Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior

- Frequency Spectrum for the Normal Telemetry Behavior from a GPS Satellite



Adapting Fourier Analysis for Predicting On-Orbit Space Vehicle Equipment Telemetry Behavior



- **Conclusion**
  - Earth, Lunar and planet orbiting satellite's equipment telemetry behavior mimics harmonic behavior and so RF and digital signal theory can be used to quantify and predict normal telemetry behavior
  - Equipment telemetry behavior can be predicted using Fourier analysis to identify accelerated aging in equipment telemetry and stop surprise equipment failures that occur on space vehicle decreasing risk
  - Some equipment failures occur well within normal telemetry operating range with accelerated aging in data making it difficult to identify leading to total loss of a satellite
  - Space vehicle equipment failures can be prevented by having expected telemetry behavior available for comparison with actual

FA

Failure Analysis

Creek Bridge Business Complex
12 Glen Falls Circle
Salinas, CA 93906
www.failureanalysisco.com
sales@failureanalysisco.com
info@failureanalysisco.com

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