Prognosis and health monitoring applications in satellite systems

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ABSTRACT: The purpose of this communication is to review the applications of prognosis and health monitoring in satellite systems. It provides an insight into the problematic of using housekeeping information for prognosis and health monitoring. This challenge is particularly relevant in the spatial domain as it relates to operations, service removal with de-orbiting with respect to the LOS (Law on Space Operations) or the kick-off of new programs. In addition to the decision-making aspect, it relates to the diagnosis (identification of the state of the system) and prognosis (future degradation assessment and residual lifetime).

1 INTRODUCTION: ISSUES OF HEALTH MONITORING ON SPACE SATELLITES

The "Health Monitoring" covers the monitoring of a system health, continuously or intermittently from direct or indirect observations, to anticipate and make better decisions.

Beyond the borders of its original field of predictive maintenance, "Health Monitoring" seeks to increase system availability while reducing costs, trying to improve:

- Diagnosis (identification of system status)
- Prognosis (future degradation assessment and residual lifetime) from the diagnosis but also the knowledge acquired at the current time, including feedback on components or similar equipment's,
- Support for decision.

Moreover, the spatial domain has its own specificities:

- Satellites are non-repairable systems in orbit, except downloadable software, but can be reconfigured by activating embedded redundancies.
- The radiation environment and the presence of micrometeorites or mono atomic oxygen, proper to space, leads to specific failure modes (wear and fugitive failures of components, deterioration of material properties…)
- Observability of the satellite state is limited to telemetries originally planned during the design, in very small numbers by the constraints of weight and radiofrequency link capacity,
- The satellite's lifetime is relatively long (5 to 20 years) as well as that of their development cycles (3 to 10 years),
- The construction of satellites in very low series is within the field of prototyping and can hardly lead to the production of a collection of exploitable lessons learned data.

The decision support in the field of satellites concerns:

- Operations which relate to the exploitation, monitoring and possible actions of satellites reconfiguration,
- Withdrawal of service under LOS (Law on Space Operations), which now requires to deorbit satellites at the end of their mission (release of a position on the geostationary orbit or controlled reentry or reentry within 25 years)
- Kick off of new programs providing sustainable functions or services, such as Earth observation or the provision of radio channels for example.

The economic stakes of the decision-making processes that were previously carried out more or less empirical are greatly enhanced by the LOS which introduces a new decision of ending an object with still some potential, to comply with regulatory requirement.

The design process and qualification of satellites is intended to ensure an objective of mission success (reliability of 0.7 at 10 years, for example), in nominal and eventually degraded operation. It does not answer this new need of on-line decision-making support, to take sometimes well before or after the end of the mission duration originally planned.

So the interest of “Health Monitoring” in this context seems obvious, although its implementation, to monitor the state of a complete satellite and to model all the degradation phenomena, shows itself particularly complex.

This is why the CNES (French Space Agency) tries, first, to raise all the methodological difficulties of this improvement of the knowledge and the decision-making before considering operational use on its systems.

2 METHODOLOGY OF IMPLEMENTATION

From a state of the art of the theoretical models of degradation and their implementation, raised by specialists from academic world, and a census of all degradation phenomena currently observed on satellites, ambition of this study is to associate appropriate theoretical model with each phenomenon, and then group them together to form a kind of macro model of degradation of a complete satellite.

Every component degradation phenomenon of a satellite has been previously subject to a characterization, by interviewing experts of different disciplines and by exploiting available data from feedback experience in operation or test.
Opportunities to observe these phenomena in orbit by direct or indirect information channels were also identified as well as additional means which can improve their visibility.

Moreover, the contribution of health monitoring in operation should be estimated a priori to size at best the resources which are dedicated to it. So, it is planned to develop behavioral simulators of space systems, based on satellite architectures and degradation models established.

3 BRIEF OVERVIEW OF THE STATE OF THE ART CONCERNING DEGRADATION MODELS

The modeling of a degradation process can be done in various ways.

In absence of any observation of the phenomenon, reliability models, such as the Weibull law, can be obtained from statistical data of failure on similar products. Allowing estimating the probability of failure after given operation duration, these models can be completed by acceleration models to take into account environmental conditions of the concerned element.
The problem of the reliability estimation turns off different when a product is subject to a degradation process which can be quantified in the time and to which an operating limit threshold of operation can be set. It is then possible, to follow the evolution of the aforementioned process in tests, to assess the predicted reliability of the product, or during the operational life of the product, to know its health from day to day and act accordingly.

By observing the deviations of deteriorations per unit of time, the phenomenon can be modeled by a Gamma process, if the degradation is always increasing (monotonous deterioration), or by a Wiener process if degradation can be reduced temporarily by improvement phenomena and even healing [1]. The degradation phenomenon can be stationary or non-stationary and be influenced by environmental conditions.

In absence of direct observation, some degradation phenomena can be modeled by a hidden Markov process. Proposed by Leonard E. Baum (1965), this one describes a Markov process for which states, representative of levels of progressive degradation, are partially observable through probabilistic indicators (a vibrational spectrum or a color of oil will give for example information about the state of degradation of a mechanism). The Viterbi algorithm is then used to find the most likely sequence of transitions from a sequence of observations and the Forward-Backward algorithm, also named as Baum-Welch, to estimate the parameters of the model.

Other phenomena can be modeled by Piecewise Deterministic Markov Process (PDMP). Developed by Davis (Davis 1984), this type of dynamic reliability hybrid process can combine random characteristics with continuous components in interaction (environmental variables which are going to influence and be influenced by the system, for example).

The use of dynamic Bayesian network can also be considered to model degradation processes. It allows representing the evolution of random variables according to a discrete sequence.

4 DEGRADATION PHENOMENA OF SATELLITES

A typology of equipment’s subject to degradation phenomena on a satellite has been established.

4.1 *Solar generator*

The solar generator (SG) is used to produce electrical energy in orbit. Fixed or movable relative to the satellite, in order to move towards the sun, it is made up of solar cells connected in series to form strings, themselves connected in parallel to form sections.

The SG is dimensioned during design phase according to the need of power at end of life. In addition to the sizing uncertainty in the beginning of life (3%), it is considered damage by UV and micrometeorite (0.25% / year) and degradation due to radiation (1% / year). However, the nature and extent of the damage depends on the satellite's orbit.

In terms of observability, the loss of a cell has almost no effect due to the presence of bypass diodes, and the loss of a string is not immediately visible on the battery charge current in the absence of a converter MPPT (Maximum Power Point Tracking) to exploit the SG at its maximum power. Monitoring the state of charge of batteries can inform on the state of degradation of SG, however taking into account changes in consumption of the mission.

4.2 *Propulsion subsystem*

The propulsion subsystem is used for the orbit control of the satellite (station keeping) and the deorbiting at the end of the operational life.

Two types of propulsion are mainly used.

4.2.1 *Chemical propulsion*

Chemical propulsion is obtained by sending propellant (typically hydrazine), at a specific pressure in a combustion chamber containing a catalytic bed.

Therein, a chemical reaction takes place and produces gases ejected towards a thruster.

Types of damage encountered are due to high thermal constraints on the catalyst and to radiation of any pressure sensors and electronic parts which may cause a return of inconsistent information.

In terms of observability, the monitoring of the specific thrust impulse (Isp) which characterizes the efficiency of the thruster, gives a good indication on the health status of the thruster.

The measure of the force needed to change trajectory (ΔV) is estimated in real time depending on the position of the satellite and compared with the theoretical ΔV. This correlation allows real highlighting degradation of the propulsion subsystem.

4.2.2 *Electrical propulsion*

Ion propulsion technology is among the most widely used electric propulsion systems. It is obtained by ionization of a propellant fluid, and by acceleration of the ions by means of an electrostatic field.

A gas (typically xenon) is injected into the cathode and the anode block. Some of the electrons provided by the cathode are injected into the magnetic field generated by the coils and enter in collision with xenon atoms, which are ionized and ejected by the thrust axis of the satellite.

The erosion of the walls of the ceramic discharge channel caused by the spray of ions and electrons and the wear of the cathode are the main degradation phenomena of ion propulsion.

Concerning observability, three characteristics predominate:

- The reference potential of the cathode (CRP), which represents the state of health of the cathode,
- Flow of xenon, which determines the discharge current. A lower rate compared to the nominal flow is characteristic of a performance of the propulsion system.
- The oscillation of the current, which reflects the instability of the plasma and, compared to the expected curve, is the wear indicator / damage of the engine.

The interpretation of ΔV is identical to that of chemical propulsion.

4.3 *Mechanisms*

Mechanisms are used to modify the geometry of a part of the satellite to ensure a given function.

There are two types of mechanisms, those performing movements of translation (magnetic bearings, flexible blades) and those performing movements of rotation (sliding bearings, magnetic bearings, slip rings, ball bearings).

Mechanisms present in a satellite are designed for vibration resistance and suffer significant efforts during the launch into orbit. The main degradation phenomena encountered are due to friction efforts.

Magnetic bearings are inherently devoid of friction.

Sliding bearings are used as single-shot systems (for example, deployment of solar panels generator). Their use is reduced to a short operation; they suffer no degradation caused by the space environment.

As well as the flexible blades, the slip rings are subject to fatigue phenomena. They are sized during design phase. Any malfunction can only be assigned to a design problem. The space environment has no direct impact on these mechanisms.

The main degradation phenomenon of the ball bearings concerns the deterioration of lubrication over time. In case of defect related to lubrication, degradation mechanism is extremely fast (on the order of a few days).

In terms of observability, mechanism degradation will result in increased friction reducing performance. For the same movement, a higher torque will be required. Yield loss will result in local temperature increase. Telemetries concern the current consumption and the temperature.

4.4 *Battery*

Accumulator batteries currently used on satellites are lithium-ion technology. They consist of cells in series (string), themselves connected in parallel. Adding additional strings relative to need help offset the loss of some of them.

These batteries deteriorate in terms of capacity and internal resistance.

After an initial degradation in storage, higher if the battery is charged or if the temperature is high, the battery capacity decreases with the number of charge and discharge cycles. This degradation depends on the depth of discharge (DOD) and the temperature of the battery.

In terms of observability, the battery capacity is difficult to measure in orbit unlike its electromotive force at full load, which is also an indicator of degradation.

4.5 *Thermal control*

Thermal control is designed to keep the satellite in a temperature range for the nominal operation during the different phases of a mission and to limit the temperature gradients between different points of a structure or equipment.

There are two ways to perform the functions of temperature control: passive thermal control and active thermal control.

The passive thermal control is present on the outer surfaces of the satellite. Insulation blankets (Mylar or Kapton) can be used to avoid the effects of thermal cycling and thereby maintain a constant temperature. Radiators with coating defined according to the need for heating or cooling are also used (playing on their absorptivity and emission ability of solar flux and albedo). Finally, the arrangement of equipment's in the satellite, according to their operating temperature, should be consistent. Degradation phenomena are considered on the coatings of radiators. They meet aging phenomena due to UV, photonic, electronic radiation, and atomic oxygen, according to orbit. These degradation phenomena have the effect of modifying the emissivity properties of coatings and therefore their power of emission or absorption.

The active thermal control concerns the use of heaters enslaved by thermostats to increase temperature. No degradation phenomenon is considered.

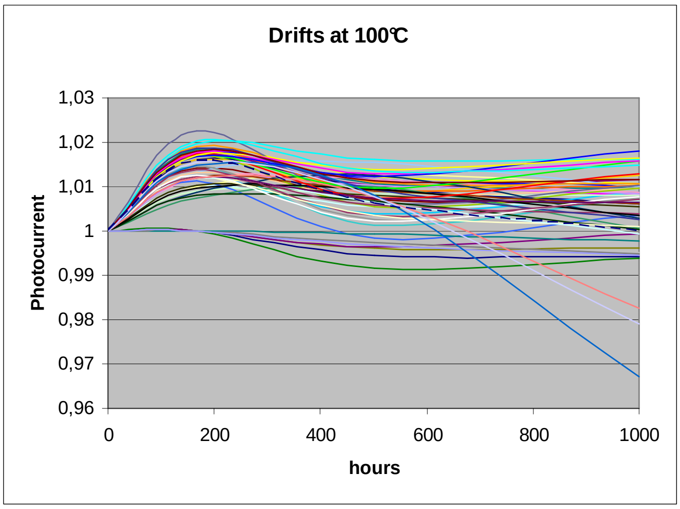
In terms of observability, the presence of multiple temperature sensors in a satellite allows monitoring the performance degradation of the thermal control.

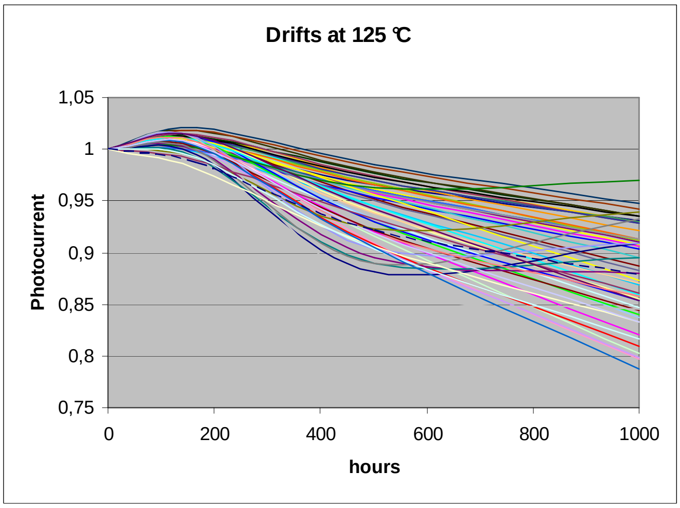
5 MODELING OF A DEGRADATION PHENOMENA

5.1 *Phototransistors current drift*

As an example, we present, below, how the degradation of the phototransistor current drift, used in optical sensors of gyroscopic actuator can be modeled by a nonlinear Wiener process. It is associated with an acceleration law to take into account the satellite temperature evolution due to the progressive degradation of its radiators.

Data from life tests of these phototransistors at different temperatures (100 °C, 126 °C and 160 °C) are shown in Figure 1. This shows the evolution of current from measurements performed at 0, 168, 500 and 1000 hours.





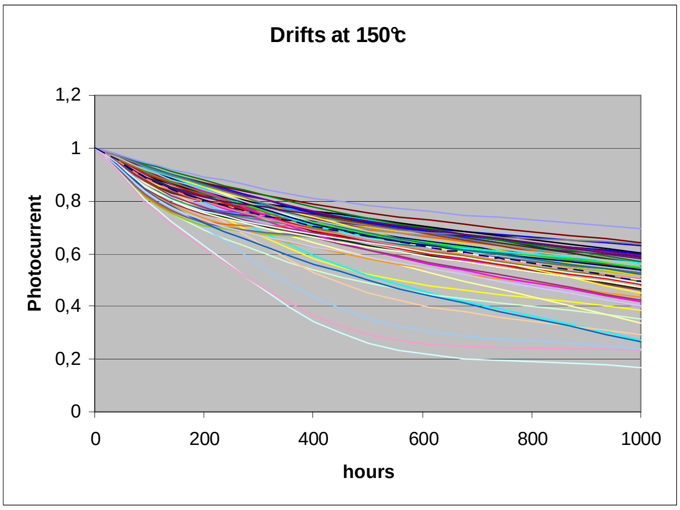


Figure 1. Evolution of phototransistors current at different temperatures

5.2 *Nonlinear accelerated Wiener process*

A Wiener process W(t) describes a trajectory of degradations which evolutions between successive instants are independent and not always of the same sign (degradation or improvement).

This process is linear trend m and variance σ^2 if:

- W(t) is a stochastic process with independent increments with continuous trajectories
- W(0)=0
- For all t>0 and Δt>0, the increment law $W(t+\Delta t)-W(t)$ is a normal law $N(m\Delta t,\sigma^2\Delta t)$ of density :

$$f(x)=\frac{1}{\sigma\sqrt{2\pi.\Delta t}}e^{\left(-\frac{(x-m.\Delta t)^2}{(2\sigma^2.\Delta t)}\right)} \quad \text{for t>0} \qquad (1)$$

Note that such a process has got for expected value $E[W(t)]=mt$ and for variance $Var[W(t)]=\sigma^2 t$

This process expresses linear degradations on average. To make this process nonlinear, it is necessary to use an increasing function m(t) such as $m(t)=pt^q$ with p and q≥0 for example, and to operate the replacement of $m\Delta t$ by $m(t+\Delta t)-m(t)$.

The increment law $W(t+\Delta t)-W(t)$ is then a normal law $N(m(t+\Delta t)-m(t),\sigma^2\Delta t)$ of density:

$$f(x)=\frac{1}{\sigma\sqrt{2\pi.\Delta t}}e^{\left(-\frac{(x-(m(t+\Delta t)-m(t)))^2}{(2\sigma^2.\Delta t)}\right)} \quad \text{for all t>0} \quad (2)$$

The estimation of parameters of the function $m(t)$ and σ can be made by the method of maximum likelihood whose expression is:

$$L(m,\sigma^2)=\prod_{i=1}^{n}\prod_{j=1}^{q_i}\frac{1}{\sigma\sqrt{2\pi\Delta t_{ij}}}e^{-\frac{(\Delta W_{ij}-(m(t_{ij})-m(t_{i(j-1)})))^2}{2\sigma^2\Delta t_{ij}}} \qquad (3)$$

To take into account the environmental conditions in the estimation of the degradation, it is possible to integrate a stress factor in the modeling.

In the manner of Accelerated Life Standards models [2], it is supposed that stress affects the degradation curve by a scale factor, while it remains in the qualification field of the product.

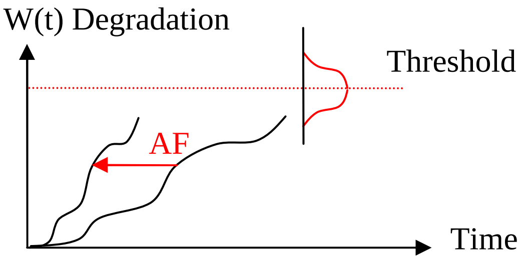


Figure 2. Representation of the influence of the acceleration Factor

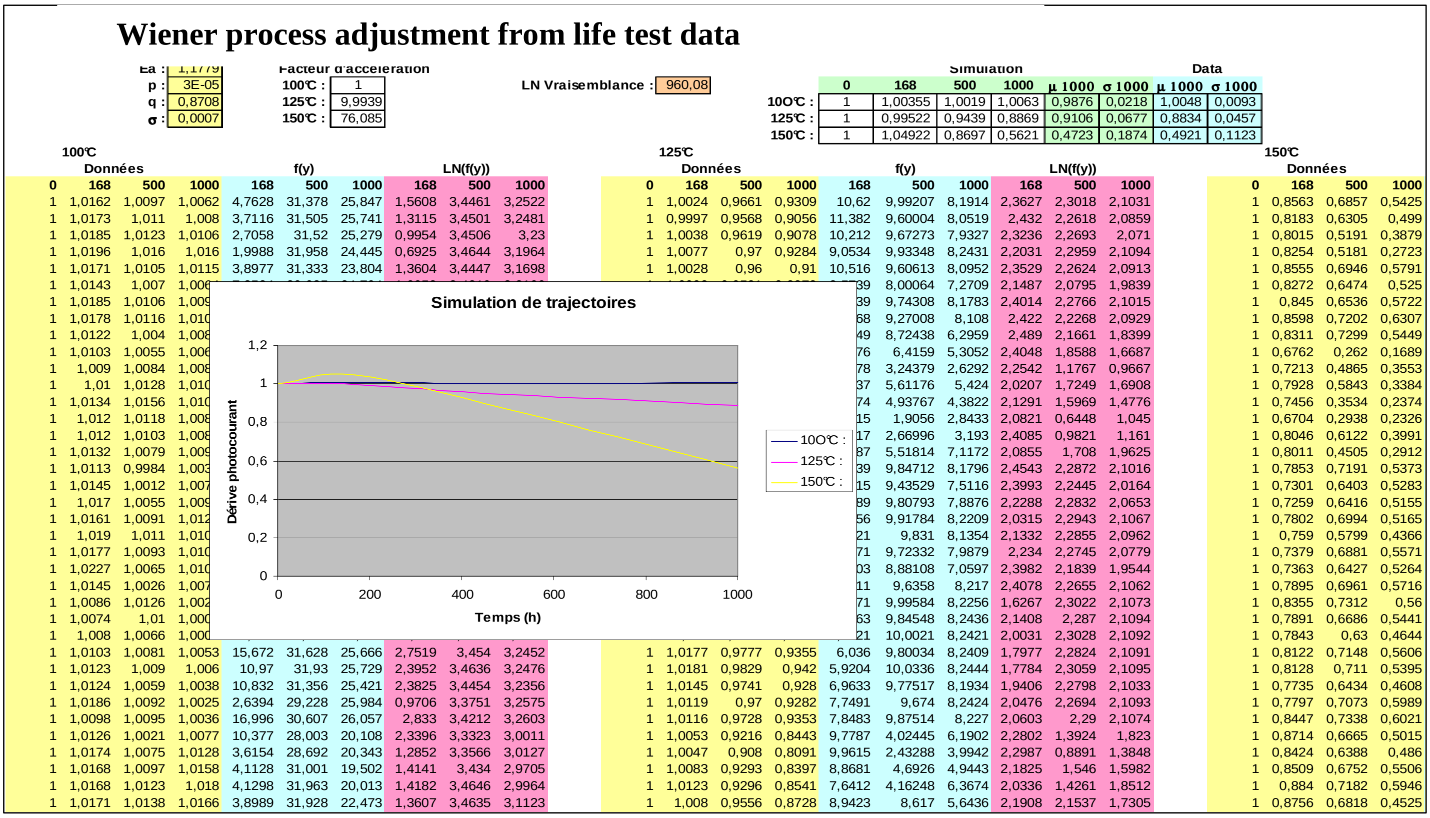
The increment law $W(t+\Delta t)-W(t)$ becomes a normal law conditioned by the acceleration factor FA : $N(m(FA.(t+\Delta t)-m(FA.t),\sigma^2.FA.\Delta t)$.

For the temperature acceleration, the Arrhenius factor $FA=e^{\left(\frac{Ea}{K}.\left(\frac{1}{273+100}\right)-\frac{1}{273+T^\circ}\right)}$,referenced to 100°C was used with the activation energy Ea (unknown) and K, the Boltzmann constant (8.6171 10^{-5} eV/°K).

5.3 *Model adjustment*

The four parameters of the nonlinear accelerated Wiener model have been adjusted from test data by the method of maximum likelihood (Figure 3). This adjustment was achieved through a global optimization tool (GENCAB from CAB INNOVATION), which can overcome the multiple optima of the logarithm of the likelihood function [3].

From experience feedback data, on-line observation of the current of a phototransistor, on board environmental conditions and their evolution, and the knowledge of operating threshold, then it is possible to predict at any time the remaining life of this component, or rather its reliability in a near or distant future.



Wiener process adjustment from life test data

Ea : 1,1779
p : 3E-05
q : 0,8708
σ : 0,0007

Facteur d'accélération
100°C : 1
125°C : 9,9939
150°C : 76,085

LN Vraisemblance : 960,08

	Simulation						Data	
	0	168	500	1000	µ 1000	σ 1000	µ 1000	σ 1000
10O°C :	1	1,00355	1,0019	1,0063	0,9876	0,0218	1,0048	0,0093
125°C :	1	0,99522	0,9439	0,8869	0,9106	0,0677	0,8834	0,0457
150°C :	1	1,04922	0,8697	0,5621	0,4723	0,1874	0,4921	0,1123

100°C

Données				f(y)			LN(f(y))		
0	168	500	1000	168	500	1000	168	500	1000
1	1,0162	1,0097	1,0062	4,7628	31,378	25,847	1,5608	3,4461	3,2522
1	1,0173	1,011	1,008	3,7116	31,505	25,741	1,3115	3,4501	3,2481
1	1,0185	1,0123	1,0106	2,7058	31,52	25,279	0,9954	3,4506	3,23
1	1,0196	1,016	1,016	1,9988	31,958	24,445	0,6925	3,4644	3,1964
1	1,0171	1,0105	1,0115	3,8977	31,333	23,804	1,3604	3,4447	3,1698
1	1,0143	1,007	1,006						
1	1,0185	1,0106	1,009						
1	1,0178	1,0116	1,010						
1	1,0122	1,004	1,008						
1	1,0103	1,0055	1,006						
1	1,009	1,0084	1,008						
1	1,01	1,0128	1,010						
1	1,0134	1,0156	1,010						
1	1,012	1,0118	1,008						
1	1,012	1,0103	1,008						
1	1,0132	1,0079	1,009						
1	1,0113	0,9984	1,003						
1	1,0145	1,0012	1,007						
1	1,017	1,0055	1,009						
1	1,0161	1,0091	1,012						
1	1,019	1,011	1,010						
1	1,0177	1,0093	1,010						
1	1,0227	1,0065	1,010						
1	1,0145	1,0026	1,007						
1	1,0086	1,0126	1,002						
1	1,0074	1,01	1,000						
1	1,008	1,0066	1,000						
1	1,0103	1,0081	1,0053	15,672	31,628	25,666	2,7519	3,454	3,2452
1	1,0123	1,009	1,006	10,97	31,93	25,729	2,3952	3,4636	3,2476
1	1,0124	1,0059	1,0038	10,832	31,356	25,421	2,3825	3,4454	3,2356
1	1,0186	1,0092	1,0025	2,6394	29,228	25,984	0,9706	3,3751	3,2575
1	1,0098	1,0095	1,0036	16,996	30,607	26,057	2,833	3,4212	3,2603
1	1,0126	1,0021	1,0077	10,377	28,003	20,108	2,3396	3,3323	3,0011
1	1,0174	1,0075	1,0128	3,6154	28,692	20,343	1,2852	3,3566	3,0127
1	1,0168	1,0097	1,0158	4,1128	31,001	19,502	1,4141	3,434	2,9705
1	1,0168	1,0123	1,018	4,1298	31,963	20,013	1,4182	3,4646	2,9964
1	1,0171	1,0138	1,0166	3,8989	31,928	22,473	1,3607	3,4635	3,1123

125°C

Données				f(y)			LN(f(y))		
0	168	500	1000	168	500	1000	168	500	1000
1	1,0024	0,9661	0,9309	10,62	9,99207	8,1914	2,3627	2,3018	2,1031
1	0,9997	0,9568	0,9056	11,382	9,60004	8,0519	2,432	2,2618	2,0859
1	1,0038	0,9619	0,9078	10,212	9,67273	7,9327	2,3236	2,2693	2,071
1	1,0077	0,97	0,9284	9,0534	9,93348	8,2431	2,2031	2,2959	2,1094
1	1,0028	0,96	0,91	10,516	9,60613	8,0952	2,3529	2,2624	2,0913
				39	8,00064	7,2709	2,1487	2,0795	1,9839
				39	9,74308	8,1783	2,4014	2,2766	2,1015
				68	9,27008	8,108	2,422	2,2268	2,0929
				49	8,72438	6,2959	2,489	2,1661	1,8399
				76	6,4159	5,3052	2,4048	1,8588	1,6687
				78	3,24379	2,6292	2,2542	1,1767	0,9667
				37	5,61176	5,424	2,0207	1,7249	1,6908
				74	4,93767	4,3822	2,1291	1,5969	1,4776
				15	1,9056	2,8433	2,0821	0,6448	1,045
				17	2,66996	3,193	2,4085	0,9821	1,161
				87	5,51814	7,1172	2,0855	1,708	1,9625
				39	9,84712	8,1796	2,4543	2,2872	2,1016
				15	9,43529	7,5116	2,3993	2,2445	2,0164
				89	9,80793	7,8876	2,2288	2,2832	2,0653
				56	9,91784	8,2209	2,0315	2,2943	2,1067
				21	9,831	8,1354	2,1332	2,2855	2,0962
				71	9,72332	7,9879	2,234	2,2745	2,0779
				03	8,88108	7,0597	2,3982	2,1839	1,9544
				11	9,6358	8,217	2,4078	2,2655	2,1062
				71	9,99584	8,2256	1,6267	2,3022	2,1073
				63	9,84548	8,2436	2,1408	2,287	2,1094
				21	10,0021	8,2421	2,0031	2,3028	2,1092
1	1,0177	0,9777	0,9355	6,036	9,80034	8,2409	1,7977	2,2824	2,1091
1	1,0181	0,9829	0,942	5,9204	10,0336	8,2444	1,7784	2,3059	2,1095
1	1,0145	0,9741	0,928	6,9633	9,77517	8,1934	1,9406	2,2798	2,1033
1	1,0119	0,97	0,9282	7,7491	9,674	8,2424	2,0476	2,2694	2,1093
1	1,0116	0,9728	0,9353	7,8483	9,87514	8,227	2,0603	2,29	2,1074
1	1,0053	0,9216	0,8443	9,7787	4,02445	6,1902	2,2802	1,3924	1,823
1	1,0047	0,908	0,8091	9,9615	2,43288	3,9942	2,2987	0,8891	1,3848
1	1,0083	0,9293	0,8397	8,8681	4,6926	4,9443	2,1825	1,546	1,5982
1	1,0123	0,9296	0,8541	7,6412	4,16248	6,3674	2,0336	1,4261	1,8512
1	1,008	0,9556	0,8728	8,9423	8,617	5,6436	2,1908	2,1537	1,7305

150°C

Données			
0	168	500	1000
1	0,8563	0,6857	0,5425
1	0,8183	0,6305	0,499
1	0,8015	0,5191	0,3879
1	0,8254	0,5181	0,2723
1	0,8555	0,6946	0,5791
1	0,8272	0,6474	0,525
1	0,845	0,6536	0,5722
1	0,8598	0,7202	0,6307
1	0,8311	0,7299	0,5449
1	0,6762	0,262	0,1689
1	0,7213	0,4865	0,3553
1	0,7928	0,5843	0,3384
1	0,7456	0,3534	0,2374
1	0,6704	0,2938	0,2326
1	0,8046	0,6122	0,3991
1	0,8011	0,4505	0,2912
1	0,7853	0,7191	0,5373
1	0,7301	0,6403	0,5283
1	0,7259	0,6416	0,5155
1	0,7802	0,6994	0,5165
1	0,759	0,5799	0,4366
1	0,7379	0,6881	0,5571
1	0,7363	0,6427	0,5264
1	0,7895	0,6961	0,5716
1	0,8355	0,7312	0,56
1	0,7891	0,6686	0,5441
1	0,7843	0,63	0,4644
1	0,8122	0,7148	0,5606
1	0,8128	0,711	0,5395
1	0,7735	0,6434	0,4608
1	0,7797	0,7073	0,5989
1	0,8447	0,7338	0,6021
1	0,8714	0,6665	0,5015
1	0,8424	0,6388	0,486
1	0,8509	0,6752	0,5506
1	0,884	0,7182	0,5946
1	0,8756	0,6818	0,4525

Figure 3. Adjustment from degradation data

6 EVALUATION OF THE HEALTH MONITORING CONTRIBUTION ON A SATELLITE SYSTEM

Contribution of Health Monitoring, as well as the possible addition of embedded hardware facilitating its implementation, must be estimated a priori in order to size the resources dedicated to it. Also, it is intended to simulate the evolution of satellites degradation, from established models, in order to assess the impact on the whole exploitation duration.

Similarly, the development of behavioral simulators extended to all satellite systems (constellation), even on the process development of replacement systems, initiated from the state of the currents systems, is considered to evaluate this contribution in terms of availability and cost of the service provided on a long-term slippery horizon.

The development of such simulator, for a constellation of four satellites with simplified models of degradation, has already allowed considering substantial gains brought by Health Monitoring, both in terms of time cost of the provided service as its quality (significant decrease of long-term interruption risks). Indeed, a satellite service in long-lasting vocation presents risks of interruption in case of early failures of the existing system or in case of development issues of the replacement program. Similarly, there are risks of use of overabundant resources, with additional operation costs.

7 CONCLUSION

Because of its complexity and limited observability, the health follow-up of a complete satellite covering diagnosis and prognosis, will never be perfect.

However, it can be improved to help the decision making with strong economic stakes taking into account regulatory requirements imposed to limit congestion in orbit.

Trying to raise all the difficulties of this new approach, CNES hopes to significantly improve the way of operating satellites in the future.

The complete results of this methodological study on the Health monitoring are planned for the end of 2013 and should later lead to operational use in orbit.

REFERENCES

[1] Baussaron J., Mise au point de modèles prédictifs de fiabilité dans un contexte de dégradation associé à des profils de mission, thèse de doctorat, 2001.

[2] Nikulin M., Gerville-Reache L., Couallier V., Statistique des essais accélérés, Hermes science, Lavoisier, 2007.

[3] Cabarbaye A, Tanguy A, Bosse S (2012), Adjustment of complex probabilistic models and estimation of confidence intervals in a discrete manner, ESREL, Helsinki.