

Accurate Battery Performance Modelling: The Key to Accessing a Truly Responsive Modular Small-Cell Concept

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ABSTRACT: The AEA Technology (AEA) Small Cell concept allows an infinite range of battery sizes to be built up using the minimum amount of re-qualification. Furthermore, an extensive rolling stock of cells is held at AEA to ensure that future demand can be met without the need for programme delays due to cell manufacture lead-time. Batteries can be composed of modular blocks so that energy storage systems can be built up from common building bricks. This eliminates the need for qualification and minimises recurring battery cost. Such features have captured the mood of the small satellite community in the quest for a truly responsive space capability. However, the Small Cell concept can become even more responsive if battery-modelling software is leveraged. This paper demonstrates how.

Batteries play a key role during spacecraft Integration and Test (I&T), as they are fundamental to the power subsystem and critical to spacecraft health and safety. Typically, spacecraft manufacturers procure a workhorse battery. This battery (as a minimum) is electrically representative of the flight model. This need for additional hardware has a cost and schedule impact so that its replacement by accurate battery modelling software is highly attractive. Moreover, mishandling during I&T can result in the need for additional workhorse batteries and schedule delays. It is therefore seen that, for the small satellite community to truly progress towards the rapid checkout of multiple spacecraft, accurate modelling tools are essential.

For small satellites to meet the rapid deployment targets of the user community, interface standards must be agreed so that development time is minimised. Traditionally, spacecraft manufacturers have stipulated a minimum capacity to space battery manufacturers. However, many alternative definitions of capacity exist (both by battery suppliers and their customers) making performance comparison difficult. This slows down acquisition and design activities. It is proposed that the most intuitive way to express battery performance is by demonstrating that the minimum battery terminal voltage over life supports the operating voltage of all on-board avionics units. In order to demonstrate such performance for any given mission load profile, flexible and accurate software must be available.

AEA have developed a software suite that allows battery performance to be predicted with an unparalleled degree of confidence. Battery configuration, mission duration, type (LEO, GEO etc) and operating conditions are input and the software outputs all key battery performance parameters including terminal voltage, current and thermal dissipation. Results are output in transparent form, directly accessible through common engineering tools such as EXCEL. Both AEA and our customers utilise the software and confidence is provided by the fact that software had been verified against long-term in-orbit telemetry. The use of modelling software approach expedites system design, battery requirements definition and design reviews.

1. BACKGROUND

AEA Technology has a long established reputation for high accuracy analysis and prediction supporting the performance of delivered flight hardware. The approach, developed with product lines such as tribology, radiometric calibration systems, UHF antenna and cell by-pass devices, has been strongly maintained for lithium-ion batteries.

Validation of in-house modelling tools that support battery-sizing analysis has been a key part of AEA's rapid development in the lithium-ion battery market for space. Specialised tools are

described and demonstrated in [1] and [2] to model and explain inter-cell behaviour such as string-to-string current sharing, self discharge and natural balancing mechanisms of the Sony 18650 cell. This balancing behaviour is fundamental to the simple, s-p battery topology used in AEA battery designs, resulting in low mass, high reliability and highly customisable solutions.

The core tools *BEAST* and *LIFE* described in this paper are used in all battery sizing analyses. Extensive validation has been performed against on-ground test to give the highest level of confidence to customers in performance verification – This confidence leading to the

awarded contracts to deliver over 30 Lithium-ion flight batteries for customers in Europe, North and South America, Africa, and Asia

With Ariane flight 165, launched in December 2004, the total of launched AEA Technology Lithium-ion batteries has now increased to 14. This represents the highest number of flights of any lithium-ion battery supplier, and is testimony to the proven benefits offered with our approach. Further details of the early battery designs as used on these missions can be found in [3].

From these missions, AEA Technology has been privileged to be given access to in-orbit battery telemetry from both PROBA and Mars Express. This presents a unique opportunity to validate analysis and prediction tools against long-term realistic operating regimes.

1. AEA Lithium-ion Space Batteries

The AEA small-cell approach meets the needs of the small satellite and responsive space community for a number of reasons. In particular, the high number of existing and qualified (>20) space battery designs means that high energy density and low-cost battery hardware can be delivered on a rapid schedule via protoflight or build to print programmes.

A good example of such utilisation is with our 28V nominal 15Ah module. This battery design has been adopted on four separate space programmes encompassing fourteen spacecraft. Six spacecraft are already operating in LEO with the design giving an unrivalled pedigree. Figure 1 shows a picture of four 15Ah modules.



Figure 1 The Qualified 28V 15Ah Module

The modularity of the AEA design approach means that battery modules can be connected in parallel to build larger capacity batteries without the need for re-qualification. The Brazilian National Space Agency mission SSR-1 is utilising four 15Ah modules to build up a 60Ah battery. With the array of designs that AEA can offer, this offers a huge range of possibilities for battery sizes. However, for the needs of the responsive space community,

AEA has proven that a common standard 'battery building-brick' (such as the 15Ah) could allow great savings across programmes.

2. BATTERY MODELLING SOFTWARE

The spacecraft community can often refer to the prediction of space battery performance as a black art. The long-term prediction of battery behaviour and even the ideal operational regime for hardware has often been the subject of debate and controversy within the community. The battery is a critical item for spacecraft health and safety and, with a number of high-profile failures, the need for reliable performance prediction techniques has become a very important issue.

Since the late 1990's AEA has constructed various battery modelling tools. Originally intended for internal use as a design aid, the benefits of the software to customers quickly became obvious following excellent feedback in design reviews. As well as the obvious risk mitigation utility of such software, customers found that system level issues that were heavily impacted by the battery could be handled much better with reliable software. Examples of this are:

- Examining solar array and battery interaction effects such as bus latching at end of life following natural array degradation.
- Performing sensitivity studies to see the effect of different thermal control strategies.
- Sensitivity studies on payload operation planning. In particular, AEA has worked on a number of applications where heavy payload operation can result in substantial daylight battery discharge. In such cases, battery capability directly drives possible payload usage.
- Many system level anomalies can directly impact the battery. For instance attitude control or array tracking problems can lead to a battery operational regime fundamentally different from the original one planned. Accurate software allows contingency plans to be quickly checked prior to execution and the long-term effects to be charted.
- Training support to customers during the transition to lithium-ion from NiCd and NiH technologies.

More recently, the benefits of accurate battery modelling software in the small satellite and responsive space communities have become apparent. For example, the aim of checking out large numbers of small satellites prior to launch has pushed spacecraft manufacturers in the direction of utilising software simulation modules to replace workhorse hardware. The synergy with this idea

for battery hardware is obvious as the cost for representative workhorse batteries can become substantial as fleet size increases.

The crucial benefit of accurate modelling software to the goal of responsive is best understood when the AEA recommended philosophy for ‘six-day’ turnaround missions is considered.



Figure 2 Stockpiling Battery Modules

AEA predicts that many spacecraft manufacturers will select a standard battery brick design such as the 14V 3Ah pack shown in Figure 2. For the needs of different missions, their modular bus will be constructed in different configurations utilising standard modules. The battery will be such a module with the numbers of bricks connected in parallel suitable for the needs of each mission. The use of transparent, accurate battery modelling tools to ensure the correct battery size is selected will be crucial.

AEA battery modules can be stored for years at room temperature with minimal maintenance. Once the mission need has been received, the spacecraft builder would perform simulations to determine the minimum battery size necessary to meet mission requirements. This would then equate to a specific number of battery modules that could be selected from the stock held at the manufacturer. Buying large numbers of battery modules will save substantial cost. In actual fact, AEA are sure that the entire process from the receipt of need to installation of battery hardware on the spacecraft could be performed in less than 24 hours.

AEA modelling tools have been demonstrated on a suite of, the standard commercial cell size, 18650 cells. It is foreseen that existing qualified battery designs will be utilised by space customers with next generation 18650 cells. These cells offer increased energy and power density as well as cycle life. In order to ensure that the responsive space community can exploit these technological advances, AEA fully intends to extend battery modelling software capability.

2. AEA BATTERY SIMULATION TOOLS

The key requirement to battery performance prediction can be broken down into two main categories:

- 1) The ability to accurately evaluate changes to cell characteristics over life as a function of battery usage
- 2) The ability to predict detailed battery performance under a given operational regime, based on specific cell characteristic changes over life

The following two tools developed and used by AEA Technology for these tasks - **BEAST** and **LIFE**:

Battery Simulation Tool- **BEAST**

The software tool **BEAST** (Battery Electrical Analysis sizing Tool) was originally developed in 1998 as a ‘virtual battery tester’. In essence, the software allows definition of battery operational demands and uses differential equation solution techniques to transiently analyse how the defined battery configuration will behave.

The tool incorporates a thermal model to allow effects of cell temperature variation during operation and therefore the variation of battery internal resistance to be modelled. Inclusion of fade parameters (capacity and internal resistance) allows simulation of End of Life (EOL) behaviour to be made - thus verifying mission performance and allowing optimisation of the battery to the specified requirements.

Input Parameters	Output Parameters (versus time)
Capacity Fade	Open Circuit Voltage
Internal Resistance Increase	Terminal Voltage
Cell Configuration	Battery Current
Load Profile(s)	Battery Power
Charge Profile(s)	Internal Resistance
Battery Interface Temperature	State of Charge
Initial Cell Temperature	Cell Temperature
Initial Open Circuit Voltage	Cell Level Thermal Dissipation
Cell failures at EOL	Thermal Dissipation at Battery I/F

Figure 3 **BEAST Input & Output Parameters**

BEAST is invaluable during the design phase of a battery programme to allow predictions of key battery performance parameters such as terminal voltage and state of charge. This is of utmost importance to customers as these figures are used directly in system level design. Figure 3 gives a complete list of the **BEAST** input and output parameters.

Following such positive customer feedback, AEA Technology now supplies copies of **BEAST** to its customers to allow its use for system optimisation, overview of the sizing process, and improved

confidence in prediction. Currently registered users include EADS Astrium, ESTEC, ISRO, NASA and many American primes.

Cell-Life Modelling Tool – LIFE

LIFE (Lithium-Ion Fade Evaluator) is a cell-life prediction tool that enables accurate prediction of long-term cell-life behaviour. The algorithms utilised in the software were developed from the extensive, ongoing characterisation lifetests performed by AEA Technology. Also crucial to the generation of robust algorithms were detailed inputs of AEA lithium-ion cell chemistry specialists.

Supporting tests have been running for over six years continual duration, with varying conditions looking specifically at sensitivity to State of Charge (SoC), Depth of Discharge (DoD), temperature and cycle rate on fade over life. In conjunction with detailed knowledge of chemical degradation processes for the cell technology this provides an excellent background for a reliable accurate model.

The cell-life modelling tool evaluates independently the differing mechanisms of operational and non-operational fade mechanisms to integrate long-term conditions for overall lifetime performance.

The key capability of the tool is handling highly varying mission conditions such as mixed operational and non-operational regimes, varying temperatures, non-uniform DoDs or changing End of Charge (EoC) voltages. This is only achievable through the detailed specialist chemical knowledge of the technology combined with the vast array of supporting test data available to AEA Technology.

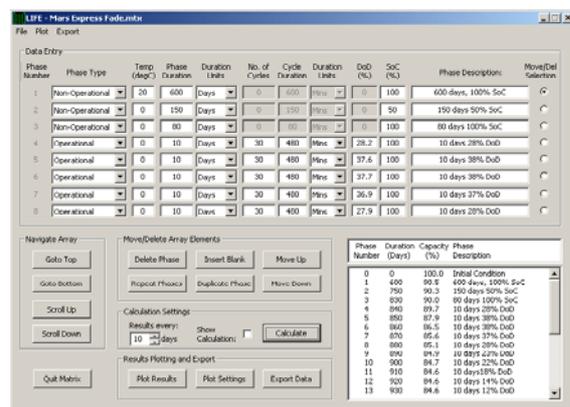


Figure 4: LIFE interface demonstrating the complex mission definitions that are possible

3. DEMONSTRATION OF SOFTWARE ACCURACY

In-orbit data from two very different missions was chosen correlation against modelling software by AEA Technology. The first, described in section 3.1 is a Low Earth Orbit (LEO) missions with a very regular charge/discharge profile. The second, described in section 3.2 is an interplanetary mission that is made up of a number of mission segments with radically different operational profiles.

3.1 CASE STUDY 1: PROBA

The Project for On-Board Autonomy (PROBA) mission contained the first ESA programme lithium-ion battery launched into orbit in October 2001. This battery, designed for a one-year-life, is still operating almost four years later after multiple mission extensions. It is the longest-serving Lithium-ion space battery.



Figure 5: The PROBA 9 Ah battery design

The 1.9 kg, 25.2 V, 9 Ah battery replaced a proposed 6.4 kg NiCd battery, significantly helping to resolve mass problems.

Constant Current, Constant Voltage (CCCV) taper charging of the battery was not implemented in the final power system for the satellite. However, despite the non-ideal charge regime, the battery is still performing well after 3.5 years in LEO operation. This operation follows two extensions to the mission from the original 1-year baseline.

3.1.1 PROBA Cell-Life Assessment

Full details of DoD variation over mission life are not available for inclusion in fade prediction. However, from the individual orbit data supplied, the DoD is known to vary between around 8 and 18%, with a nominal value of 15%

Original fade estimates made in 2002 for correlation of in-orbit performance were based directly on results from lifetests. The process consists of interpolating measured fade between

10% and 20% DoD tests for the desired cycle number. Following this, in order to account for differences in cycle rate between the tests and the PROBA mission, additional correction is then made for the ageing effects from non-operational storage tests.

The process is well verified and is the basis of fade calculations AEA Technology performs for all missions, but can be time consuming – in particular if iterations are required during a sizing or correlation process. On production of the *LIFE* tool, the process became automated, allowing rapid generation of fade prediction considering both the ageing and cycling effects automatically, to combine for a total fade prediction.

Figure 6 shows both the fade assessments made by interpolating lifetest results for specific days where data is available for performance verification, and the automatically generated results from *LIFE* for the same conditions. The high level of agreement demonstrated verifies the algorithms used within the cell-life tool to rapidly perform the long-term behaviour assessment.

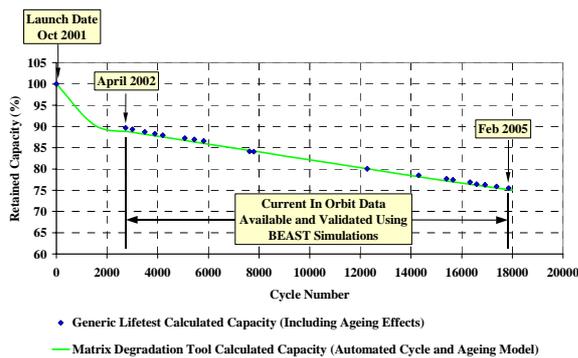


Figure 6: Lifetest and *LIFE* fade predictions for the PROBA mission

Internal resistance data increase over life is also periodically measured in AEA Technology lifetests. In a similar manner to that described for fade prediction it can be interpolated for consideration of PROBA performance. This is shown in Figure 7, along with calculated resistance from *LIFE*.

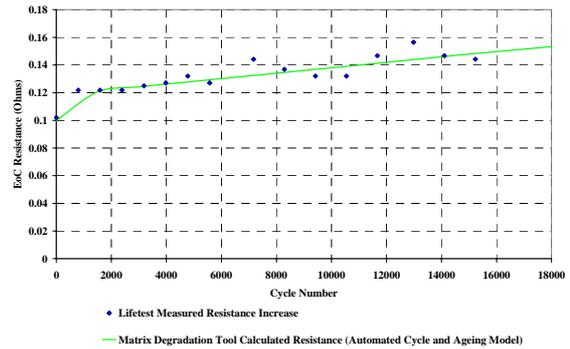


Figure 7: Lifetest and *LIFE* resistance increase predictions for PROBA mission

3.1.2 PROBA Performance Correlation

Once fade predictions and resistance increase over life is available from *LIFE*, simulations for any time of life can be generated using *BEAST*. The basic steps of the process are described below and shown in Figure 8:

- 1) Telemetry for battery current is retrieved from telemetry data file
- 2) Charge and discharge currents are combined into a single Excel csv file of current v's time
- 3) Temperature data from telemetry is reviewed to determine I/F temperature for battery for simulation
- 4) Initial voltage data from telemetry is used to estimate initial EMF for orbit simulation performed
- 5) Capacity and resistance degradation parameters are inputted into *BEAST* based on time through mission
- 6) Simulation is run and results compared

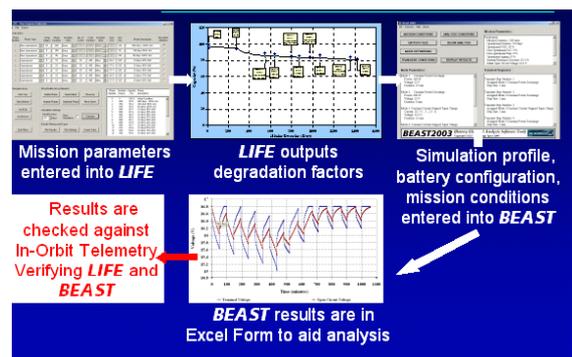


Figure 8 In-Orbit Telemetry Comparison Verifies both *BEAST* and *LIFE*

For the PROBA mission, the raw in-orbit telemetry requires a number of corrections prior to use for simulations. This is primarily due to location of telemetry measurement. For example, current is measured at the 28 V bus side of the power regulators. The current values are therefore calculated using battery voltage compared to bus voltage, in conjunction with the respective regulator efficiencies. Additionally the voltage

telemetry is corrected for a 200 mV offset, plus a voltage drop along harness line (between battery and measurement point) that is a function of charge or discharge current. These factors have been determined by ESA and Verhaert with support from AEA Technology, and are included in data supplied to AEA for performance verification.

Sample results of performance are given in Figures 9, 10 and 11. The first two figures give an early correlation during 2002, and the most recent data from February 2005 (after more than three years in LEO) is shown in Figure 11.

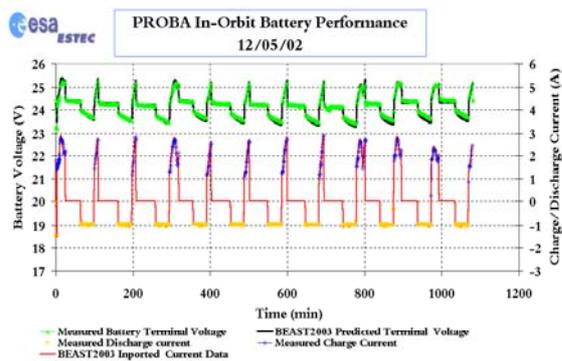


Figure 9 Correlated PROBA performance in April 2002

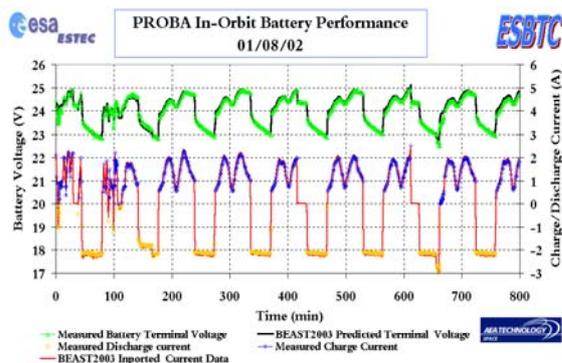


Figure 10: Correlated PROBA performance in August 2002

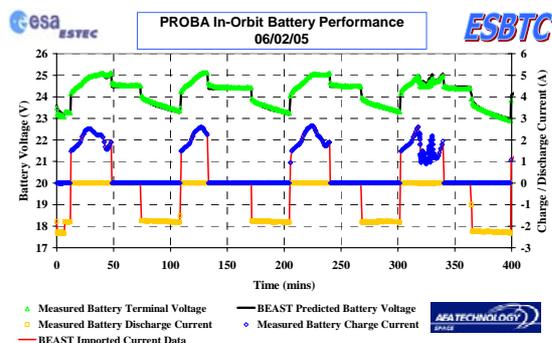


Figure 11 Correlated latest available PROBA performance Data in February 2005

In each case, data is taken from the in-orbit telemetry to generate the current v's time profiles for use in *BEAST*. The April 2002 simulation in particular shows the impact of disabled taper charge regime, and resulting periods on non-operation.

Correlation levels for the simulation, using the fade parameters shown earlier, are excellent. Typically the simulation agrees to better than 50 mV of the calculated battery terminal voltage. Worst-case uncertainty is still better than 0.1 V, with slight conservatism in prediction.

Key features of the simulation performed are:

- Regular, predictable fade used based directly on interpolated lifetest measurements, confirmed by automated fade tool *LIFE*
- Similarly predictable internal resistance increase used based on lifetest and fade tool
- Complex time varying profile for current is well captured in predicted voltage response form *BEAST*
- Performance simulation validation for periods of over 3 years in-orbit operation

3.2. CASE STUDY 2 - MARS EXPRESS

The Mars Express mission followed Rosetta as the second ESA cornerstone mission awarded to AEA Technology. The power system consisted of three separately controlled batteries that combined form a 1.5 kWh total energy storage – considerably larger than the PROBA design.

Due to both the orbit, and the spacecraft reorientation for data transmission to earth, the DoD for the battery is highly variable over mission life. The 6 month cruise phase to Mars was performed at reduced 50% SoC for life optimisation, with the battery essentially non-operational. Combined with a period of 600 days fully charged ground storage before launch, this results in a highly complex mission fade assessment.

3.2.1 Real-time Mars Express Lifetesting

Due to the highly variable operation, dedicated lifetests were performed for the Mars Express mission. In addition to accelerated tests simulating operational periods only, a real-time test is still underway. This test has now accumulated nearly 4.5 years of operation on a half sized battery. The test includes repeated representative orbit types selected from mission planning to accumulate worst case numbers of cycles of various DoD's, in addition to incorporating the mission periods of non operation.

The complexity of operation is illustrated in the lifestest voltage data shown in Figure 12 where sets of different mission operation are seen to run sequentially after each other.

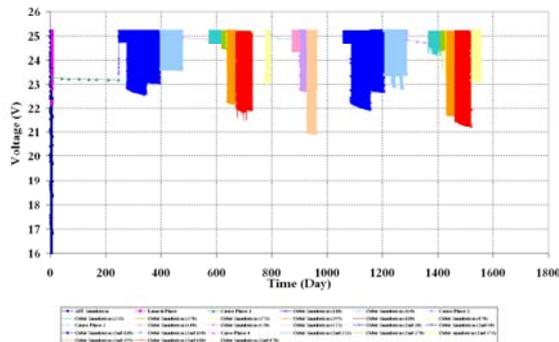


Figure 12 Complex variable operation lifestest implemented for Mars Express mission support

Creating this model in *LIFE* allows verification of predictive accuracy for highly variable mixed operating and non-operating regimes as illustrated in Figure 13. All capacity predictions are within 2% of measured, with the exception of the value at day 1070 which followed a significant test pause with the test battery left discharged and non-operational. A temporary recovery of lifestest measured capacity relative to the previous value is seen. This is a commonly occurring feature following low SoC storage and is related to stabilisation of internal diffusion processes.

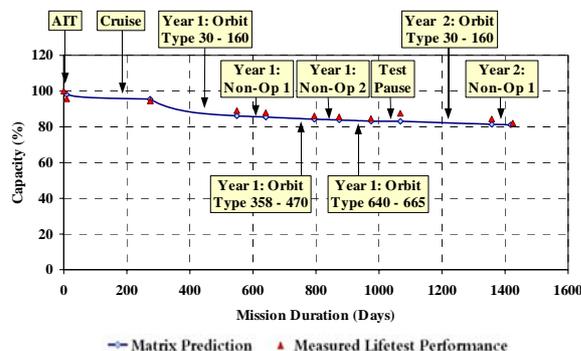


Figure 13 Compared lifestest capacity measurements and *LIFE* prediction for the real-time MEX lifestest

3.2.2 Cell-Life Assessment

Correlation of fade against lifestest data provides a high level of confidence for lifetime performance of the Mars Express mission. However, in-orbit telemetry now allows direct fade assessment on actual mission conditions.

In addition to the extended fully charged ground storage, not originally planned, an updated fade prediction can use the actual battery temperature

over life (close to 0°C, compared to the 20°C lifestest), and accurate tracking of DoD throughout the mission.

The variable nature of operation can be clearly seen in Figure 14, along with the data fit model used in *LIFE*. The screenshot shown earlier in Figure 15 shows part of this defined model (a total of 25 phases were defined for the full simulation up to February 2005).

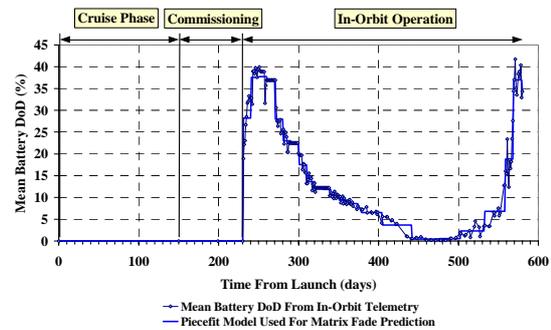


Figure 14 Variable DoD data from MEX in-orbit telemetry, and piece-fit model used for fade assessment

The resulting prediction presented in was used for correlation of performance in the four sets of detailed data made available to AEA Technology

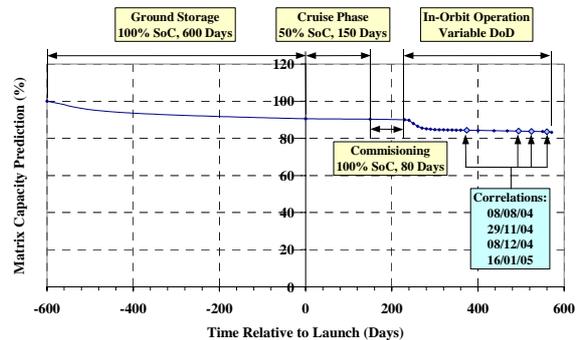
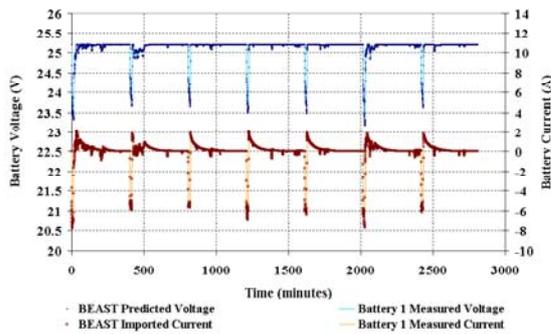


Figure 15 Updated fade prediction based on in-orbit data

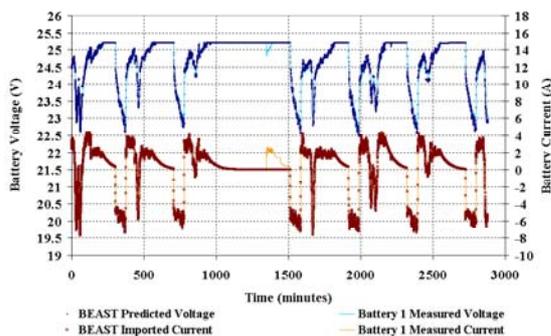
3.2.3 Battery Performance Correlation

The *BEAST* simulation process follows closely that described for the PROBA mission. No correction of telemetry was required, and simulation was actually performed separately for each battery, utilising the slightly differing temperatures of each. For clarity of results however, data is presented only for battery 1 in this paper.

Correlation of the first and the last data set supplied have been selected and shown in Figure 16 and Figure 17 since they conveniently capture low and high DoD operation of the battery due to eclipse period variation.



**Figure 16 Correlated low DoD performance
(Aug 2004)**



**Figure 17 Correlated high DoD performance
(Jan 2005)**

As for PROBA, the correlation shows an excellent level of prediction, demonstrating valid long-term fade predictions for a complex varying mission profile. One anomaly that should be mentioned is around 1400 minutes of the Jan 2005 data in which an error in telemetry data has lost information regarding an additional discharge after 1000 minutes. As a result, in the simulation performed, the battery does not require the recharge current seen from 1400 to 1500 minutes.

4. CONCLUSION

The ability to perform accurate long term prediction of spacecraft power systems is essential for optimisation of flight applications and achieving the goal of six-day mission turnaround. The battery forms a key part of the power subsystem, and the ability to model its behaviour is vital. In particular, the increasing drive for mass reduction strongly coupled with the proven capabilities of lithium-ion, combined with increasingly complex payload operation, often supporting solar array power for peak demands requires sophisticated tools.

It is obvious that specialised tools such as *BEAST* and *LIFE*, used in conjunction with system level power models can benefit the space industry in achieving demanding performance goals with the highest level of accuracy. In particular, the

interaction of fade assessment, and the direct simulation prediction is fundamental to understanding and accurately modelling battery operation over life.

Development continues with these tools – existing iterations of *BEAST* have already incorporated customer requested features to simplify use or enable more complex situations to be considered. A new version of *BEAST* is currently in development incorporating a more detailed thermal model that includes thermostatically controlled heaters, multiple conductive and radiative heat transfer sources that can be time varying in temperature. Integrating graphing routines implemented in *LIFE* will also be used to speed up evaluation of results.

Additionally, in conjunction with testing and modelling work performed by ESBTC, incorporation of a more accurate transient diffusion model of the Sony 18650 cells is planned. At present, *BEAST* probably shows high accuracy in significant duration discharges, but can be overly conservative for short duration pulsed type loads such as SAR applications. By working with ESA on this form of modelling and development the benefit of improved accuracy for more specialised operation can be realised by customers using this technology.

5. ACKNOWLEDGEMENT

AEA Technology gratefully acknowledges the support and feedback provided by customers on analysis methods used, including requests and suggestions forwarded by users of tools such as *BEAST*.

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