Breath in, breath out
how healthy are the batteries on Mars and Venus Express?

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I. Introduction

Mars and Venus Express are operational since 2003 and 2005, respectively. Combined, this is more than 14 years in flight of two similar spacecraft, yet operating in very different environments. Both S/C had their mission extended multiple times up to now and this process continues. The spacecraft budgets were designed for the original duration (around 1000 days for each mission), and estimates on battery capacity degradation logically cover only that period. To be able to assess the current health state of the batteries, and to gather trends for predictive models, the Flight Control Team had to develop its own empirical methods based on data available from telemetry. A thorough assessment resembling laboratory conditions is not possible due to several factors: no calibration of the sensing equipment possible in-flight, no possibility to remove the battery from the circuit, no possibility to control the discharge rate, no possibility to control the thermal environment. The method developed and used consists of fitting a model of the battery voltage (based on the ‘state-of-charge vs. EMF’ curve) to the voltage measurements as obtained from telemetry. The model optimizes the initial energy capacity degradation factor and the losses due to internal resistance dissipation. To obtain significant data for analysis the operators had to plan for dedicated longer discharges, as data available from routine eclipses was not sufficient to obtain a significant excursion of the EMF curve outside its linear initial part. Following recommendations from industry, ESA specialists and documentation, the teams also decided to keep MEX and VEX batteries at a lower State of Charge (SoC) outside eclipse periods. This is done by forcing the End-of-Charge voltage which yielded (temporary) battery capacity recovery. This paper explains the methodology used and discusses the results obtained and compares the Mars Express (MEX) and Venus Express (VEX) results and degradation predictions.

II. Results

Before explaining the model we present the results it provides. By finding the capacity degradation factor and internal resistance that best fits the model to the measurements, and by applying this method consistently over subsequent experiments, we obtain a trend in the degradation. Even if we can’t be sure of the absolute value of the degradation, we get an indication of the degradation rate over time. The latter is at least as important for operations.

Table 1 Capacity Battery 2 (the most degraded) as obtained by VEX model. The value for launch was determined by ground tests by the Spacecraft integrator [4].

Date	Battery 2						
	Capacity	Loss	RMSD	Av. R_{int}	Av. Disch. Current	Av. Temp.	Voltage reached
New	24.00 Ah	0%	-	-	-	-	-
Launch (19-09-05)	22.60 Ah	5.83 %	-	-	-	-	-
DDT1 22-04-09	19.58 Ah	18.39 %	31 mV	0.172 Ω	7.67 A	12.74°	21 V
DDT2 07-06-10	18.93 Ah	21.08 %	21 mV	0.198 Ω	7.57 A	12.47°	21 V

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Date	Battery 2						
	Capacity	Loss	RMSD	Av. R_{int}	Av. Disch. Current	Av. Temp.	Voltage reached
DDT3 27-04-11	18.88 Ah	21.32 %	36 mV	0.170 Ω	7.59 A	15.82º	21 V
DDT4 31-08-11	19.08 Ah	20.47 %	20 mV	0.173 Ω	6.76 A	12.75º	22 V
DDT5 06-12-11	18.52 Ah	22.83 %	38 mV	0.184 Ω	7.49 A	16.05º	21 V
DDT6 10-04-12	18.64 Ah	22.33 %	32 mV	0.163 Ω	7.28 A	16.12º	21 V

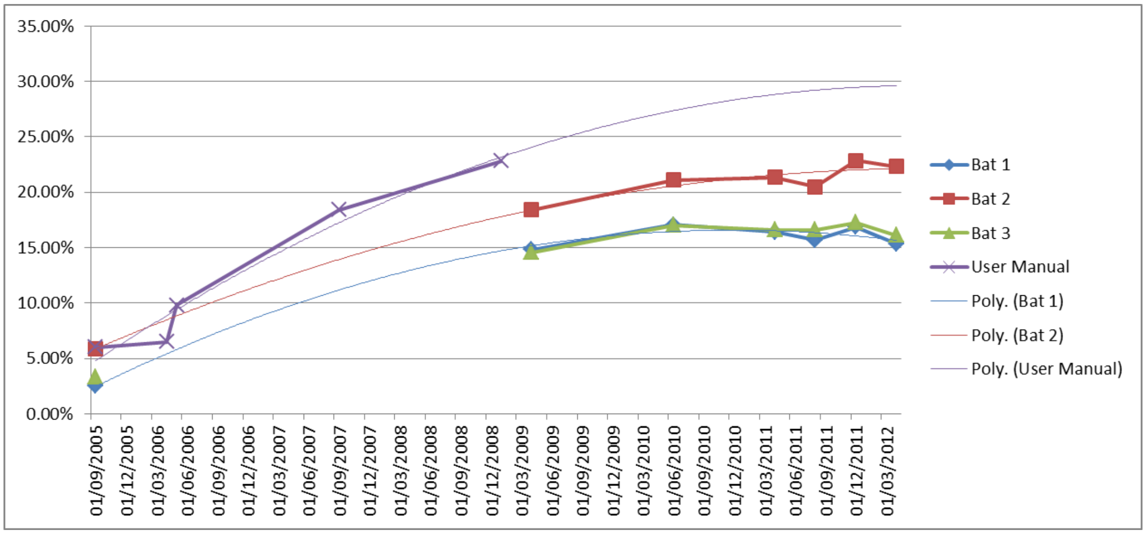

Figure 1 - Evolution of available capacity in VEX batteries

The figure above shows the trend of capacity loss, as obtained with this methodology, for VEX batteries. The lilac line shows the predicted degradation from the manufacturer user manual [5] and on top of it we see the polynomial extrapolation of that curve. One can observe apparent capacity recovery in some consecutive tests.

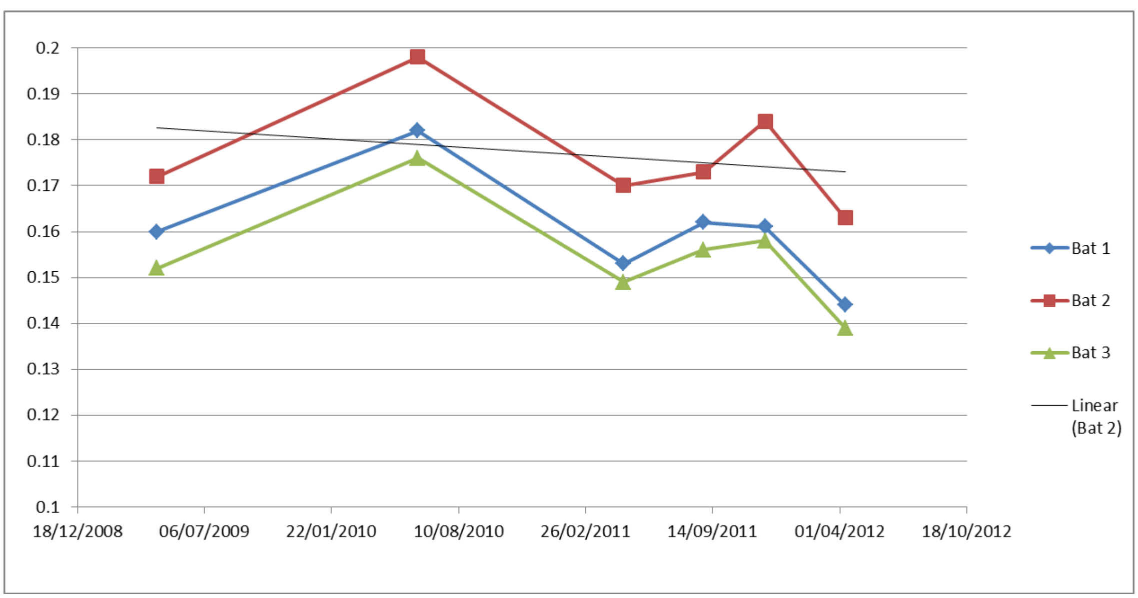

Figure 2 Evolution of estimated internal resistance

The trend of degradation in the internal resistance from this analysis is not increasing, as one would expect. On the contrary, it seems it improves with time. We don't have an explanation for this result. However, for the MEX battery (from table Table 2), ones sees an increase in internal resistance.

The figure below shows the VEX Battery 2 voltage since March 2009. The bell shaped phases correspond to eclipse seasons. The Deep Discharge tests are highlighted, and as of June 2010 one can see that the End of Charge voltage outside eclipse seasons has been lowered to 24.4 V. The same lower SoC approach is applied on MEX.

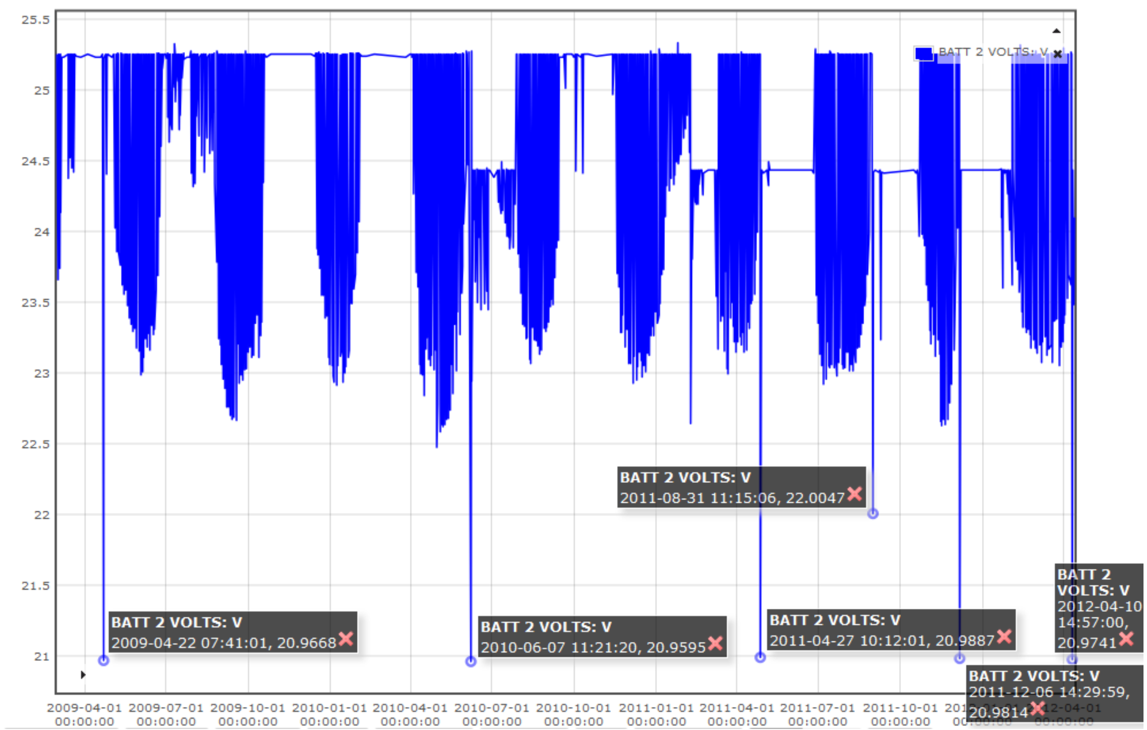

Figure 3 - VEX Battery 2 voltage since March 2009. DDT tests are highlighted.

The same methodology as for VEX was applied consistently for all the Deep Discharge Test on MEX and the results for Battery 1 are summarised below.

Table 2 Capacity Battery 1 and further test results as obtained by MEX model.

Date	Battery 1						
	Capacity	Loss	RMSD	Av. R_{int}	Av. Disch. Current	Av. Temp.	Voltage reached
New 02-06-01	24.0 Ah	0%	-	-	-	-	-
Launch 02-06-03	22.8 Ah	5 %	-	-	-	-	-
Mars arrival 05-01-04	21.6 Ah	10 %	-	-	-	-	-
Array Shadow 02-11-05	19.7 Ah	18 %	-	-	-	-	-
DDT1 22-01-08	19.2 Ah	20 %	89 mV	0.171 Ω	8.31 A	8.19°	21 V
DDT2 22-10-08	18.0 Ah	25 %	76 mV	0.182 Ω	7.66 A	5.90°	21 V
DDT3 26-06-09	17.0 Ah	29 %	41 mV	0.173 Ω	6.55 A	6.69°	21 V
DDT4 22-10-09	18.0 Ah	25 %	69 mV	0.183 Ω	7.68 A	7.10°	21 V
DDT5 22-07-10	16.8 Ah	30 %	85 mV	0.189 Ω	7.63 A	5.46°	21 V

Date	Battery 1						
	Capacity	Loss	RMSD	Av. R_{int}	Av. Disch. Current	Av. Temp.	Voltage reached
DDT6 07-05-12	16.08 Ah	33%	44 mV	0.180 Ω	6.75 A		21.48 V

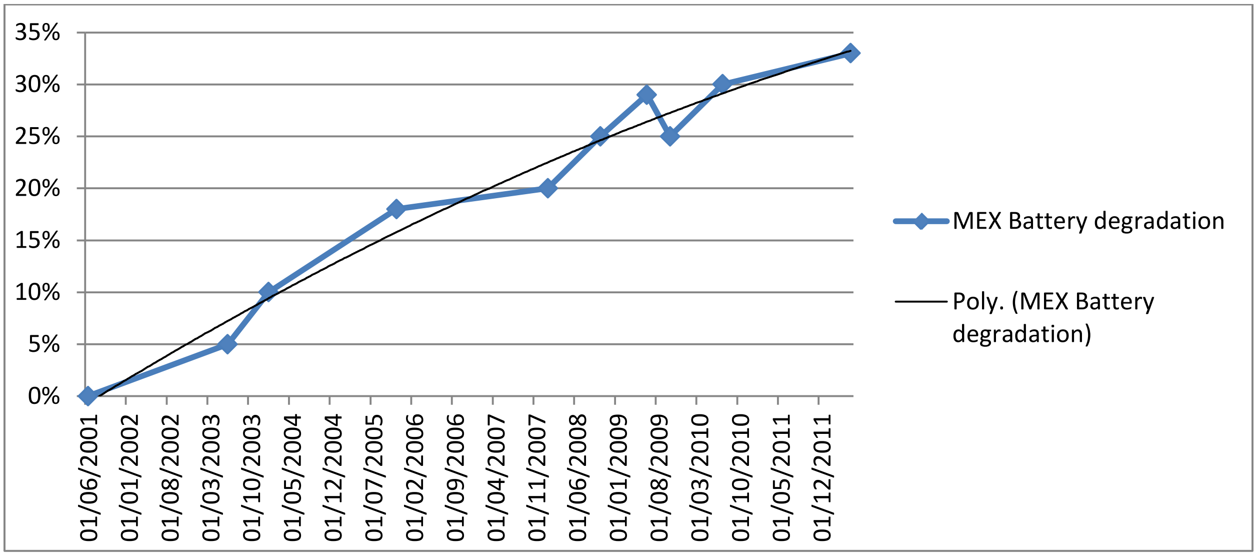

Figure 4 - Evolution of degradation of capacity in MEX battery 1 (all batteries behave similarly)

We are not able to explain why the MEX batteries, being of the same type as in VEX, show steeper variations of estimated capacity from test to test. It is clear that they show higher absolute loss than VEX because they have been in use for 2 additional years. It is worth noting that VEX battery 2 (the most degraded) belongs to the same production batch as the MEX ones.

When planning spacecraft activities, the Spacecraft User Manual requires us to manage the following constraints:
Battery minimum voltage: The spacecraft operations shall be planned such as to maintain the battery voltages nominally above 17 V for the sake of battery health purposes. In order not to interfere with the Battery Discharge surveillance (BDAS), the battery voltages should nominally be maintained above 19.6 V

Battery State Of Charge (SOC): The spacecraft operations shall be planned such as to maintain the battery SOC nominally above 30% of the nominal capacity (30% of 24 Ah per battery)[3].

Once we have determined the above model parameters (Table 1 and Table 2), namely the estimated capacity degradation and average internal resistance we can use the same model to predict what the Voltage and SOC evolution will be on a given discharge, using our best estimate for current consumption[4].

Below we show an example for an eclipse on the 19th of March 2012. The first plot shows the estimated current using the Mission Planning System model (which accounts for status of payloads and other platform systems including thermal, TT&C and AOCS) versus the actual current measured on that day from telemetry.

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[3] Because of the original uncertainty in degradation and estimation of SOC this constraint has been implemented with extra margin – above 50%, instead of 30%.

[4] It is worth noting that the current estimation is not fully deterministic because the behavior of the thermal control system is a function of the dynamic thermal environment, and this is not simple to model without a full blown thermal simulator (so we have used a simplified approach that still gives good results).

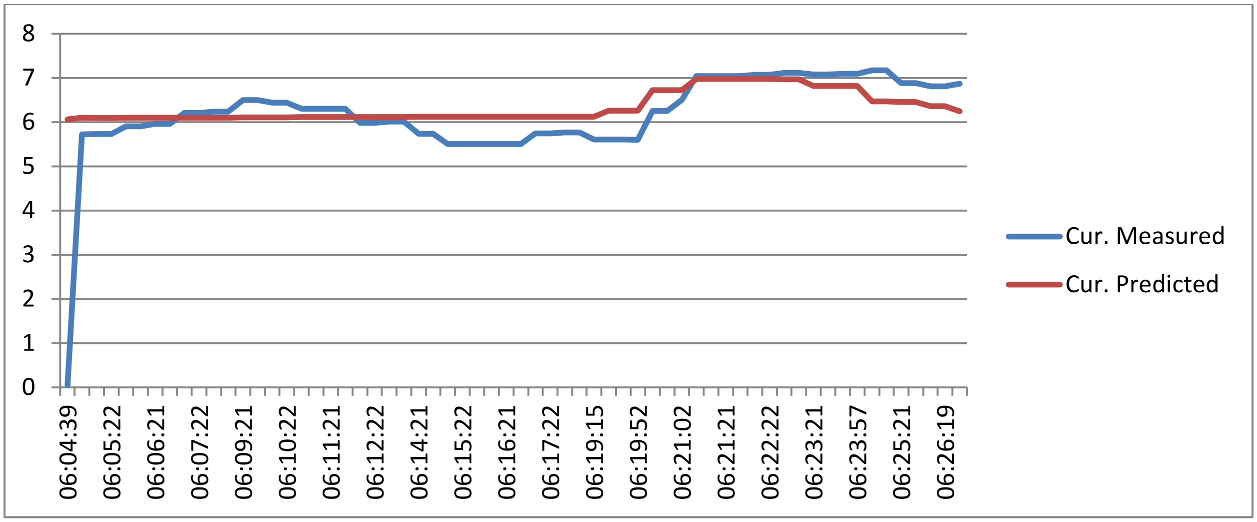


Figure 5 - Measured vs Predicted current during an eclipse on the 19th March 2012

Applying the model to the current estimation to predict the voltage we obtain the following plot (compared with the actual measured value).

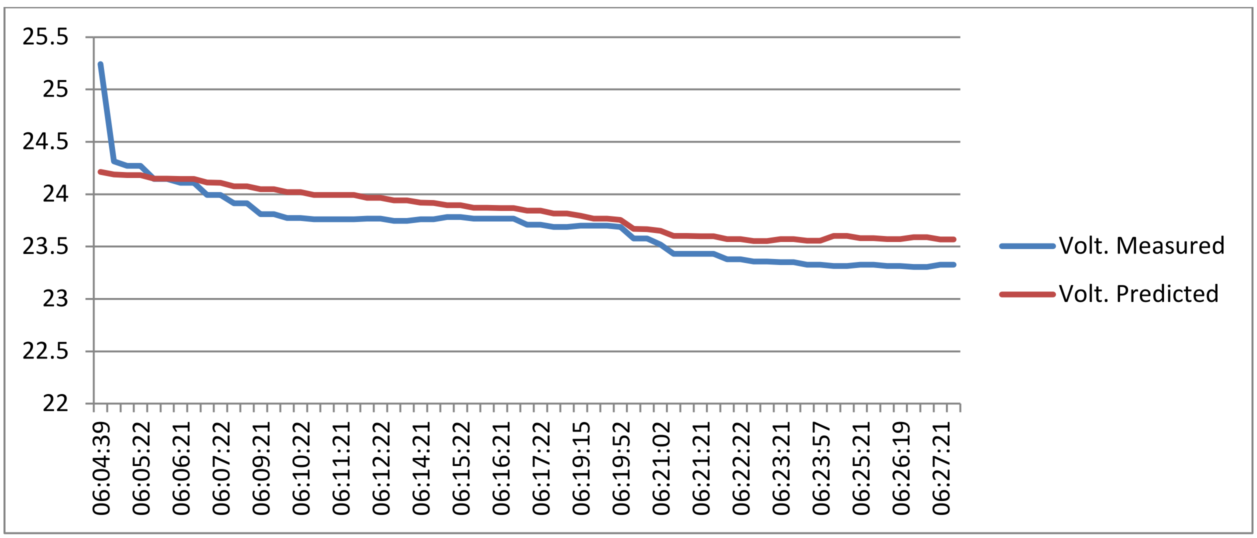


Figure 6 Measured vs Predicted voltage during the same eclipse

The RMSD obtained for this example is 0.22V which is a very good approximation and gives us confidence to plan activities safely above the threshold where a Safe Mode would be triggered (19.6 V), but with higher margins as the original manufacturer constraint allows for (that is below 50% SOC).

III. Assumptions

It is assumed [1] that the look-up table of EMF (Electromotive Force) vs. SoC (State of Charge) given by the manufacturer remains applicable even as the battery ages and its dependence of temperature is low. Linear interpolation is applied between points of the table.

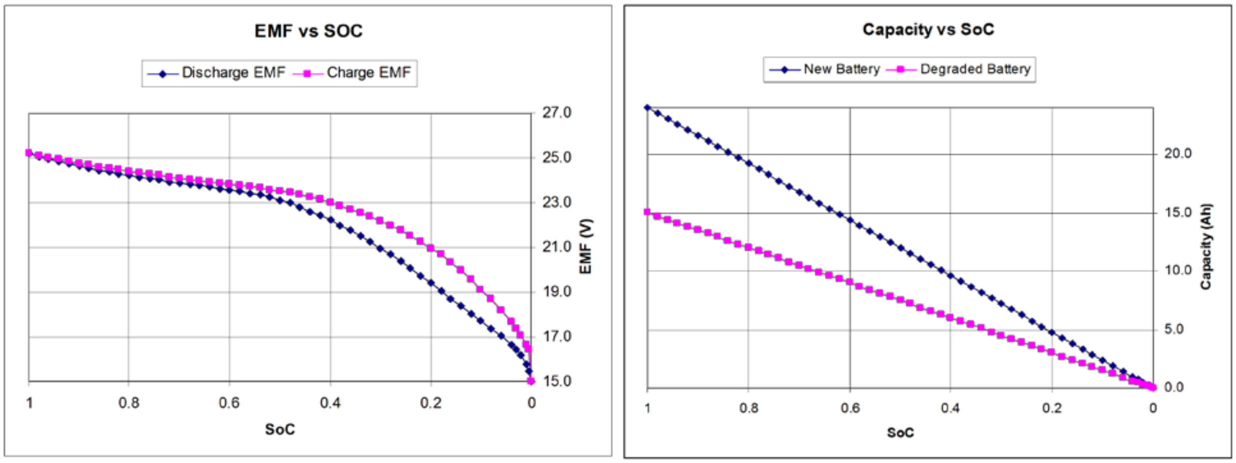


Figure 7 - EMF vs. SoC as supplied by the Battery manufacturer and example of the relation between Capacity and SoC between a new and a battery degraded by a factor of 40%

A brand new battery has a maximum current capacity of 24 Ah, corresponding to 100% SoC, as given by the manufacturer. The capacity of the battery and corresponding SoC are linearly correlated. A SoC of 80% means only 80% of the initial energy are available (in case of this battery, 19.2 Ah). A degradation of battery capacity will imply that at any moment after the production of the battery, the fully charged state will no longer correspond to the maximum 24 Ah available when new, but to some fraction of it.

A degradation factor (or capacity loss factor) will cause the corresponding Capacity-EMF curve to "shrink", thus increasing the rate of voltage drop during a discharge.

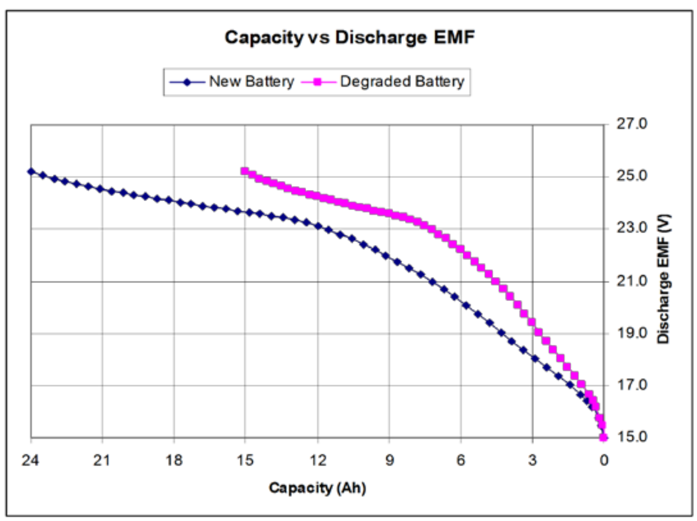


Figure 8 - Capacity vs. EMF (discharge) for a new and degraded battery

It is assumed that data measurement, conversion and precision errors are negligible. Each of the measured telemetry parameters is using 12 bits; this corresponds to the following precision of the least significant bit according to the parameters calibration:

- Voltage – 0.00732 V
- Charge Current – 0.00266 A
- Discharge Current – 0.00577 A
- Temperature – 0.0264°C

IV. The model

State of Charge Calculation

To calculate the SoC as a function of time the discharge current is integrated to obtain the capacity reduction and determine the SoC by calculating the ratio from the original energy available at the beginning of the discharge:

$$SOC(t) = \frac{\varepsilon.C_{(SOC=100\%)} - C_{flow}(t)}{\varepsilon.C_{(SOC=100\%)}} \quad (1)$$

$$C_{flow}(t) = \int_{t=o}^{t} I_{BAT}(t) \quad (2)$$

A capacity degradation factor ε is applied to the Energy at SoC=100%, this will be used for optimization of the model and to give us an idea of the battery health (we use initially a value of 1, meaning a new battery).

The integral is calculated in the following way:

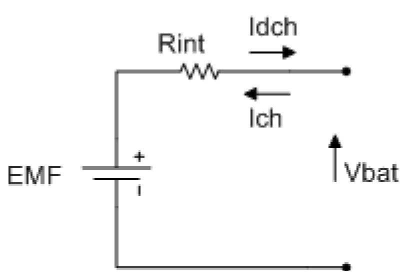
$$C_{flow}(t_i) = Av(I(t_i, t_{i-1})) \times \frac{(t_{i-1} - t_i)}{3600} + C_{flow}(t_{i-1}) \quad (3)$$

$$C_{flow}(0) = 0$$

The current I(t) is positive during discharge and negative during charge. This will result in an amount of current capacity which is subtracted in (1) from the total available at the beginning of discharge. Av() is the average function. The sampling time in seconds is converted to a fraction of the hour to be able to compute it with the energy capacity in Ah.

Battery Voltage Calculation

With the SoC, the corresponding expected EMF (discharge/charge) can be obtained by linearly interpolating from the EMF-SoC look-up table (Figure 5). Now we introduce a serial Internal Resistance (R_{int}), such that the battery EMF is degraded by a drop in this resistance.



$$V_{bat} = EMF - R_{int} \times (I_{dch} - I_{ch}) \quad (4)$$

Where:

- EMF corresponding to the calculated SoC in (1) by linearly interpolating the curve in Figure 5 (as a simplification the charge and discharge EMF have been averaged and used).
- V_{bat} is the battery voltage that we want to model
- I_{dch} is the discharge current
- I_{ch} is the charge current
- R_{int} is the internal resistance

Modeling the internal resistance

When applying this model to data available for the first deep discharge test performed with VEX batteries and letting the Excel solver optimize the ε and R_{int} parameters for the smallest RMSD error between measured and calculated battery Voltage, the following plot over time is obtained:

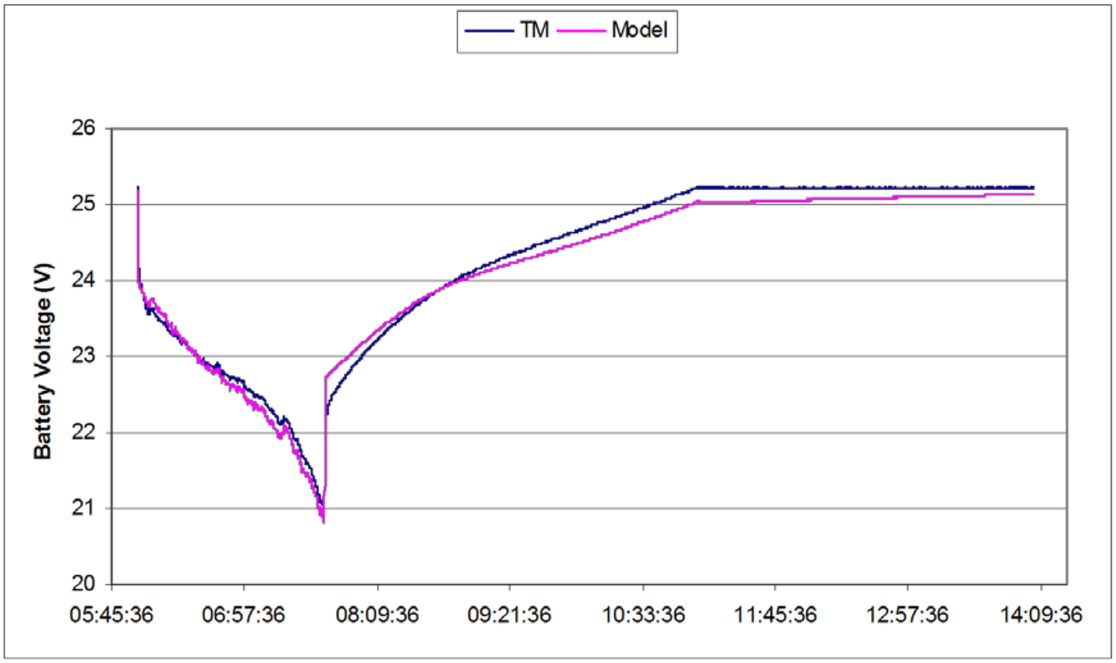


Figure 9 Battery with Internal Resistance and capacity degradation vs. Measured Telemetry

For VEX Battery 2 (the most degraded one) and for the data obtained with DDT1 as an example, this gives a value of 15.76% degradation and a constant R_{int} of 170 mΩ. The RMSD is 0.15 V, which although a good approximation, is still a considerable error as one can see in the graph.

The accuracy of the model can be improved if it is assumed that the Internal Resistance does not remain constant throughout the operation. This can be due to a dependency on temperature, current or voltage conditions, which are dynamically changing throughout the operation. Literature[1] indicates that the internal resistance decreases with temperature during a discharge.

To have a feeling for how the Internal Resistance evolves the measured voltage is subtracted from the estimated EMF and divided by the current. To estimate the EMF we assume initially that the value of capacity degradation obtained before (15.76%) still holds for the moment (but may need to be optimized later).

This gives us that the real Internal Resistance must somehow behave like showed in the following graph (the spikes around the inversion point are due to zero division):

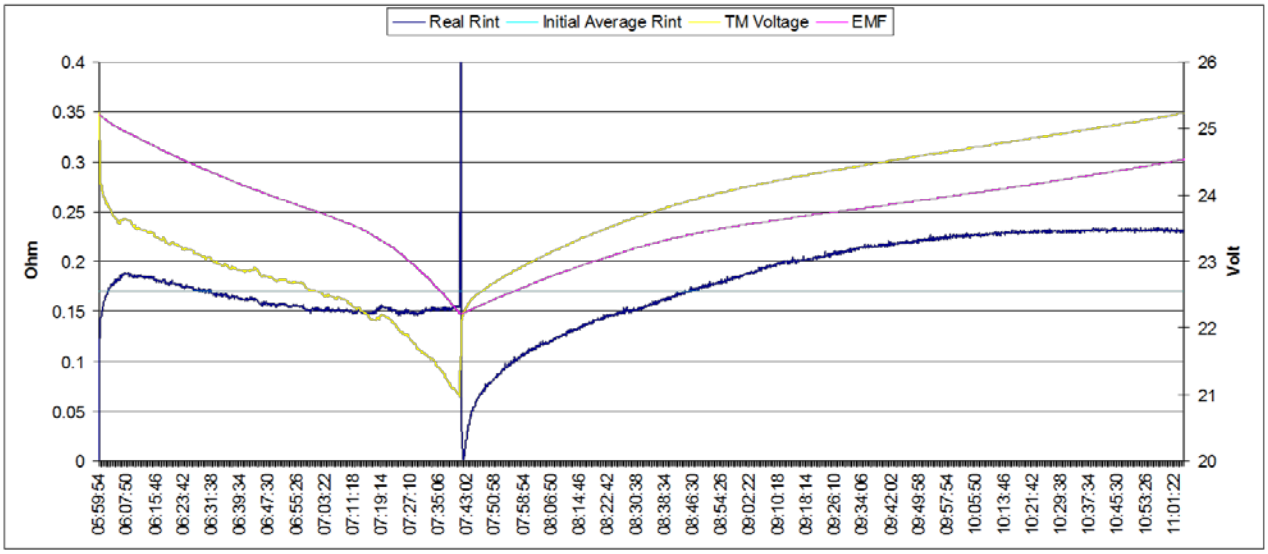


Figure 10 - Behaviour of Rint plotted against Voltage and EMF. The yellow line shows the measured voltage; the pink line the estimated EMF assuming 15.76% capacity degradation; the light blue shows the constant Rint initially calculated (170 mΩ) and the dark blue line shows the Internal Resistance calculated as the difference between EMF and Voltage divided by the current.

It seems that during the discharge the resistance tends to stabilize around an average value of 150mΩ, after an initial exponential evolution. And during the charge the Internal Resistance grows slower exponentially towards a different average value around 235mΩ.

These responses may be caused by a different behavior depending on the current direction or the different levels of current experience during discharge (between 7 and 8 A) and charge (3 A) as plotted next[5]:

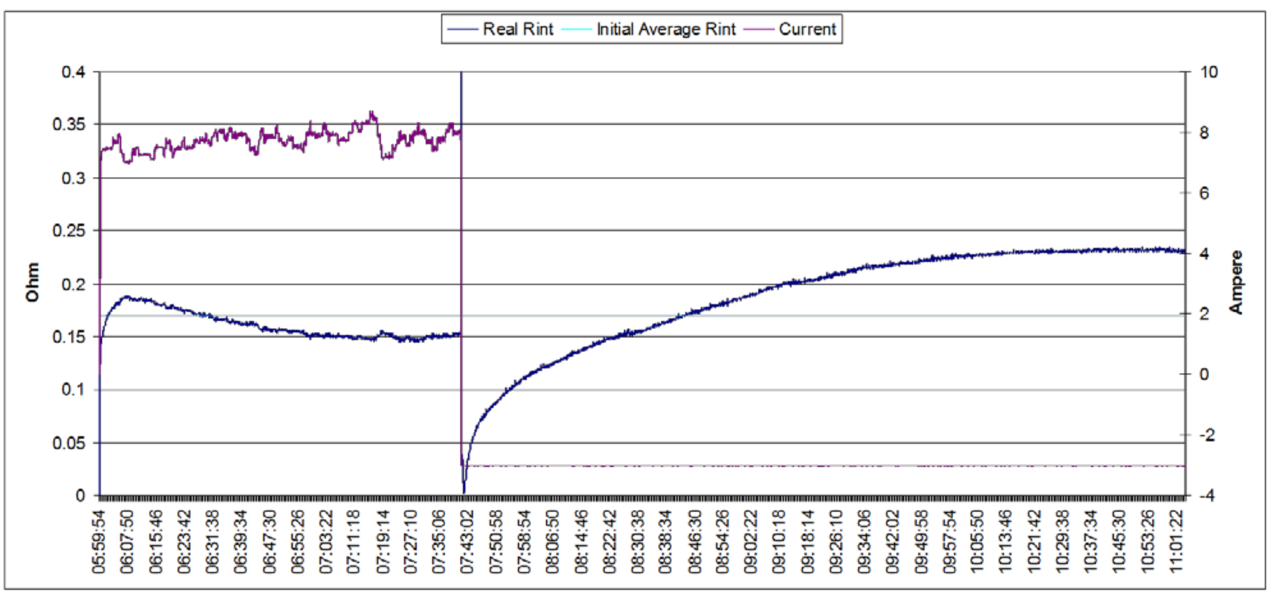


Figure 11 Behaviour of Rint plotted against the current

[5] We only look at current and voltage until the battery starts taper charging at which point the current is controlled and the result for R_{int} is no longer realistic.

To emulate the evolution of the Internal Resistance it is approximated with a line after an initial exponential transition, so we use the following generic equation with parameters:

$$R_{\text{int}}(t) = (b + m.t).\left(1 - e^{-\rho t}\right) \qquad (5)$$

With m being the line slope and b the initial value and the damping being set by ρ. We assume these parameters may have different values for charge and discharge; we let the Excel solver optimize them together with the degradation ε from equation (1).

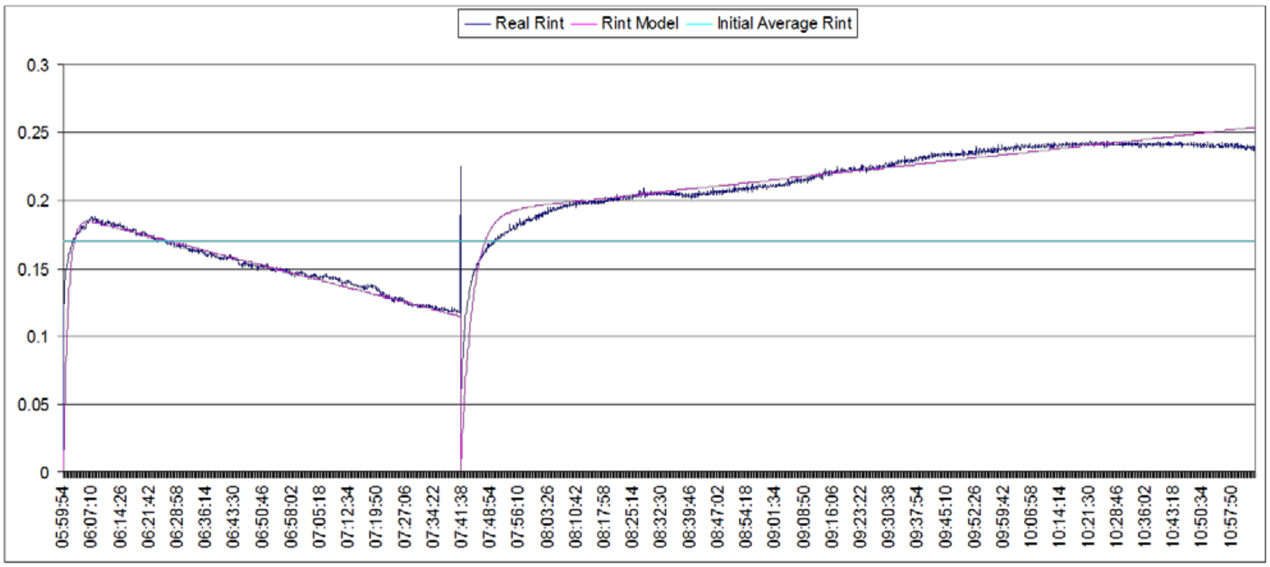


Figure 12 - Emulating the R_{int} behaviour using a step response

The dark blue line still shows the original R_{int} now obtained from telemetry voltage and estimated EMF with the capacity degradation re-optimized, and the pink line shows a modeled R_{int} by using a straight line, after an exponential transition and with re-optimization of the degradation factor.

For this particular case the following parameter values are obtained:

- ε = 18,39% (this means a current capacity available of 19,58 Ah)

Further for discharge:

- b = 0.189 Ω
- m = -0.00001131 Ω/s
- ρ = 1200

And for charge:

- b = 0.163 Ω
- m = 0.0000081 Ω/s
- ρ = 500

Using now this R_{int} equation over time (5) and the measured current (Figure 9) and the new EMF estimation with the re-optimized degradation, to model the Battery Voltage, using equation (4), and comparing it with the actual measured voltage:

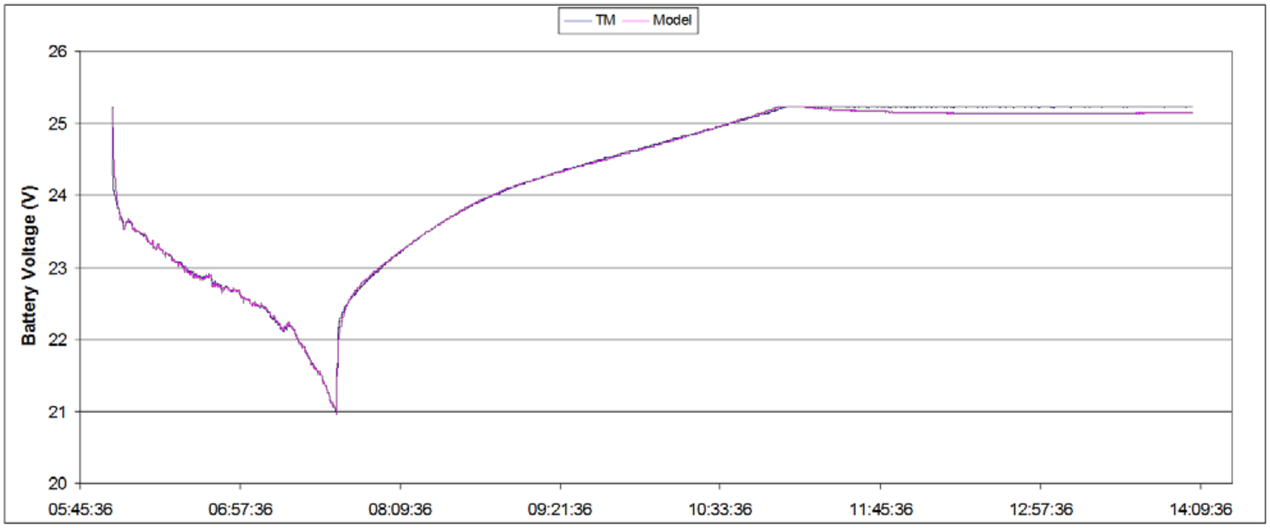


Figure 13 - Measured Voltage vs Modelled Voltage

The voltage can now be modeled based on the measured current with an error of 0.03178 V RMSD. That is, it has improved with respect to the initial constant R_{int} model by a factor of almost 5.

For each DDT test performed the parameters ε, b (charge and discharge) and m (charge and discharge) need to be re-optimize and that is what gives the evolution behavior.

V. Conclusion

The method of battery capacity characterization described in this paper has proven to be a helpful tool for the MEX and VEX flight control teams. We have shown how we can determine long term trends of the capacity evolution (which is useful for long term mission planning and approval of mission extensions) and how we can use it for short term prediction of the battery voltage behavior for activities where the power margin available is critical.

The original battery constraints, as formulated by the spacecraft manufacturer in the user manual, recommends not exceeding 50% SOC, but in fact the on-board monitoring mechanisms are looking at the voltage to decide whether over-discharge has occurred and trigger a Safe Mode.

Establishing a better relation between SOC and voltage allows us to be able to use the margin, when needed, more safely. Furthermore the formulation of the battery constraint by the manufacturer is only possible to follow if we have a good idea of what 50% SOC means after degradation has occurred over years of usage. On both counts this method helps improving the accuracy of the predictions.

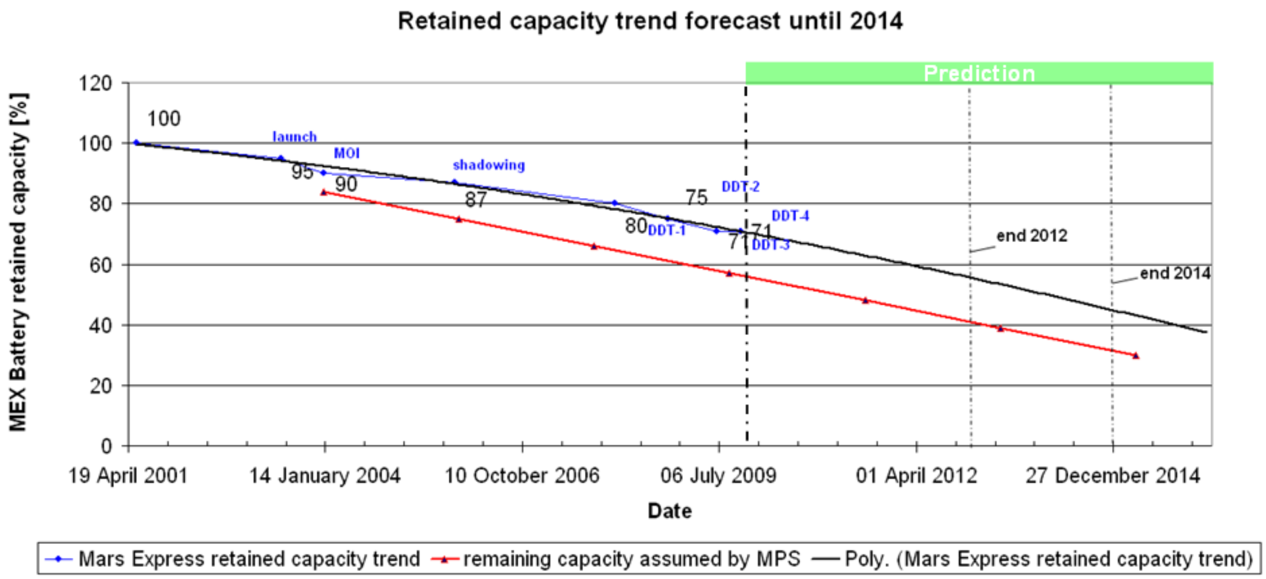


Figure 14 - Prediction of retained battery capacity for MEX until 2014

The values of capacity degradation and internal resistance cannot be interpreted in absolute terms, because they are affected by different operational environments (temperature, discharge profile, etc.) but offer a relative way to analyze the trend.

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