System engineering approach toward the problem of battery depth-of-discharge of a LEO satellite

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During the last few decades, battery Depth-of-Discharge (DoD) problem has always been a challenging and limiting factor on satellite-mission duration. This paper, from a system engineering point of view, comprehensively describes the power-hungry phases of a typical Low-Earth Orbit (LEO) satellite mission. Theses phases, each by itself or in any combination(s), may lead to high DoD levels (mainly during the eclipse phase), which will in turn shorten the mission-life, considerably. To handle the challenge most efficiently, the engineering community has developed three methodologies as:

1- Enlargement of battery capacity and/or utilization of batteries with higher allowed DoD and/or higher power-density
2- Adapting adequate/flexible mission profile(s)
3- Enlargement of solar array area and/or utilization of more efficient solar cells

This paper evaluates each of the preceding strategies by a system engineering approach .i.e.; Direct and potential inter-subsystem effects of each strategy are studied. Finally, it has

been highlighted that the final decision on which methodology to follow and the contribution of each methodology to the final approved-strategy can only be made by the means of thorough, comprehensive trade-studies and trade-offs covering all direct and potential inter-subsystem effects described in this paper.

1 Introduction

A typical _L_ow _E_arth _O_rbit (LEO) may experience as many as 14-15 eclipses during a day, in which the satellite is highly dependent on its pre-charged batteries. Logically, one may assume that too-high demands for electrical power during the eclipse may lead to the following scenarios:

1. During the first eclipse phase, the battery is discharged to some allowed Depth-of-Discharge (DoD) level. It, however, may not be fully charged during the corresponding sunlight phase. Consequently, it will enter the next eclipse phase with partially-charged batteries. This, in turn, may lead to some high DoD levels in the following few orbits. This is schematically shown in table 1.

Orbit	***Battery status upon entering the eclipse phase***	***Battery usage during the eclipse phase (Percent of total capacity)***	***Battery charge increment during the sunlight phase***
#1	100 %	- 20 %	+10 %
#2	90 %	- 20 %	+10 %
#3	80 %	- 20 %	+10 %
#4	70 %	- 20 %	+10 %
#5	may exceed the allowed DoD level	-	-

Table 1: first flight-scenario leading to excessive battery DoD level

2. The continuous required amount of electrical power is too much for the battery to supply .i.e.; the allowed DoD level will be exceeded if the battery provides the required amount of electrical power without any recharging. This case can be even worse if the satellite enters the eclipse phase with partially charged batteries.

Considering the highly-severe impacts of high battery-DoD levels, one must clearly understand the hungry phases of the mission to incorporate adequate strategies to avoid high battery-DoD levels, which will shorten the mission-life considerably.

2 Strategies to avoid high levels of battery-DoD

Theses strategies fall into the following three categories:

1. Enlargement of battery capacity and/or utilization of batteries with higher allowed DoD and/or higher power-density
2. Adapting adequate/flexible mission profile(s)
3. Enlargement of solar array area and/or utilization of more efficient solar cells

In this paper, each of the preceding strategies is discussed through a system engineering point of view. Also, the power-hungry phases of a typical LEO mission are discussed in the following sections

2.1 Enlargement of battery capacity and/or utilization of batteries with higher allowed DoD and/or higher power-density

This approach utilizes the enlargement of battery capacity so that the required level of electrical power can be accommodated within the allowed DoD level. An enlargement of the battery capacity, however, means a more bulky and heavier battery unit. Satellite missions, on the other hand, often impose stringent mass-budget allocations on the subsystems. An example of mass-budget allocation of the Swedish LEO microsatellite mission *ASTRID* is given in Table 2.

Subsystem	Unit	Mass (Kg)
Structure	Structure incl. solar panels	5.60
	Balance masses	1.36
Data Handling	ASTRID System Unit (ASU)	6.50
	Pyro unit	0.48
Radio	S-band and UHF Transmitters	0.90
	Command receiver	0.27
	Antennas + diplexer+ RF cables	1.58
Attitude Control	Magnetic torque coils	1.00
	Sun sensors	0.30
	Magnetometers	0.10
	Nutation damper	0.30
	Spin-up rocket	0.15
Power	**Cable harness**	**1.30**
	Ni-Cd battery	**2.50**
Thermal Control	Thermal blankets	0.30
Payload	Energetic Neutral Particle Imager (PIPPI)	3.14
	Electron Spectrometer (EMIL)	0.74
	Miniature Imaging Optics (MIO)	0.33
	Data compression unit (mass included in (ASU)	-
	Memory Unit (mass included in (ASU)	-
	Payload DC/DC conv. (mass included in (ASU)	-
	Payload cable harness	0.15
Total satellite		**27.00**

Table 2: Mass-budget allocation of the Swedish LEO microsatellite mission ASTRID

The obvious stringent mass-budget allocation to the Power subsystem is shown in table 1.[1] Thus, it remains to the mass-budget allocation whether enlarged-batteries (thus heavier) can be accommodated or not

Also, a second approach offers utilization of more efficient batteries, in terms of energy-density or higher allowed DoD levels. Logically, batteries with higher energy density can provide a given level of energy at a lower DoD level. Also, from [2], batteries with higher levels of DoD may not suffer from accommodating the given level of DoD. More efficient batteries, however, may be subjected to the following concerns:

1. Usually higher prices
2. Usually little or no in-orbit flight heritage
3. Accessibility of the technology: only a few number of commercial suppliers possess the corresponding technology.
4. Other undesirable characteristics: Some of the more-efficient batteries demonstrate inadequate characteristics such as explosion risks, high level of Auto-DoD, etc.

The type of battery unit incorporated to the satellite, thus, is an issue subjected to comprehensive trade-offs regarding various concerns such as: cost, reliability, performance vs. mass and accessibility [1], [2] & [3].

2.2 Adapting adequate/flexible mission profile(s)

Adequate mission profile implies operation strategies with required power-profiles which best meet the power constraints of the mission. In order to approach the challenge, most important power-consuming phases of a typical LEO satellite mission must be briefly reviewed:

-Communication:

Communication is one of the most important power-hungry phases of a LEO satellite mission (in most cases the most important one!). Power-budget allocation of the ASTRID microsatellite is given in Table 3, for comparison purposes.

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[1] The ASTRID is a microsatellite launched into LEO. It must be noted that the mass-budget allocation considerably differs from a project to another depending on various parameters such as the mission, orbit, satellite-class (from a mass point of view) and etc. Thus, this table is only meant to illustrate the stringent mass- budget allocation and is not to be generalized for other purposes.

Subsystem	Unit	Power (W)	Average power in orbit (W)
Structure	Structure incl. solar panels	-	-
	Balance masses	-	-
Data Handling	ASTRID System Unit (ASU)	5.00	5.00
	Pyro unit	-	-
Radio	**S-band and UHF Transmitters**	**16.00**	**2.60**[2]
	Command receiver	**3.00**	**0.60**[3]
	Antennas + diplexer+ RF cables	-	-
Attitude Control	**Magnetic torque coils**	**9.60**	**1.40**
	Sun sensors	0.27	0.27
	Magnetometers	0.5	0.00
	Nutation damper	-	-
	Spin-up rocket	-	-
Power	Cable harness	-	-
	Ni-Cd battery	-	-
Thermal Control	Thermal blankets	-	-
Payload	**Energetic Neutral Particle Imager (PIPPI)**	**4.08**	**4.08**
	Electron Spectrometer (EMIL)		
	Miniature Imaging Optics (MIO)		
	Data compression unit (mass included in (ASU)	1.30	1.30
	Memory Unit (mass included in (ASU)	4.00	4.00
	Payload DC/DC conv. (mass included in (ASU)	2.50	2.50
	Payload cable harness	-	-
Total satellite		-	**21.75**
Platform		-	9.87
Payload		-	11.88

Table 3: Power-budget allocation of the ASTRID microsatellite

Thus, *adequate communication pattern* (downlink/uplink) is essential to any LEO satellite project. Communication pattern can be optimized most efficiently by adequate geographical-distribution of ground-stations. It is reminded that most LEO missions often employ *Store & Forward* techniques which are highly dependent on

[2] The average transmitter power assumes that the transmitter is "ON" 16 % of the time.
[3] The command receiver is "ON" for one minute and "OFF" for four minutes to save energy.

geographical-distribution of ground-stations and the corresponding issues.[4]. Logically, if the number of ground stations is increased, the contact opportunities will be more frequent. Thus, provision of sufficient number of ground stations with adequate distribution-pattern will considerably moderate the power-load imposed by the communication scheduling/profile.[5]

- Attitude maneuvers

Attitude maneuvers do require considerable power-allocation in case of reaction/momentum wheels and other electrically-driven devices (See Table 3). Attitude control maneuvers, however, are required only at certain short periods during each orbit. Thus, mission-profile design team is meant to come up with control strategies which require minimum attitude maneuvers during the eclipse or other low-power-storage phases.

- Mission specific task

Payload is often the main power-consumer subsystem of the satellite (See Table 3). Payload power-budget allocation can be subjected to trade-studies for maximum performance vs. power. As an example, a remote-sensing mission may accomplish the requested photography of a known target with some time-delay due to some power-budget considerations and still satisfy the customer's needs. There, however, exist cases in which a time-delay for a specific task may question the level-of-merit of the whole project. As an example, a disaster-monitoring mission which comes short to do the mission-specific task (upon a request) within a given time, may not be funded at all i.e. it may be substituted by a more reliable, ready-upon-request terrestrial system. Thus, adequate trade-studies of "Performing the mission-specific task" are *highly-delicate* activities viable only through comprehensive *technical/financial/psychological trade-studies* regarding various aspects of *satellite-service revenue, end-user needs* and etc.

- Dumping of reaction/momentum wheel

It is a common practice to dump the momentum of reaction/momentum wheels by the means of electrically-fed magnetic devices. In this case, mission-profile design team is meant to come up with control strategies which perform such tasks at times in which stored-power can most easily accommodate the required power within the power-budget considerations. This, however, remains to the *A*ttitude *D*etermination and *C*ontrol *S*ubsystem (ADCS) engineers as it may lead to some extra

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[4] Tracking, Telemetry and command (TT&C) power-budget allocation is not recommended to be a subject of trade-off at this level.

[5] Provision of several ground stations with adequate geographical-distribution pattern is a challenging issue driven by various factors such as international, political and administrative state of the country and/or the corresponding agencies. This, however, is not I the scope of this paper.

requirements/constraints on ADCS in terms of hardware, software and control strategies.

- Worst hot-case conditions
Passive thermal control is the "goal-to-be-achieved" for satellite missions. Passive thermal control techniques require essentially no power-budget, thus the terminology "*Passive*" For a LEO mission, worst hot-case conditions *almost* always occur during the sunlight phase in which the satellite is mainly dependent on the generated power by the solar cells (and not the batteries). Thus, typically, worst hot-case condition is not a great concern to the problem of exceeding the allowed level of battery DoD.[6] There, however, may exist unique mission profiles in which worst hot-case conditions can build up to a concern to power-budget allocation. Thus, it is recommended that a preliminary quantitative study should be done on worst hot-case conditions.

- Worst cold-case conditions
Worst cold-case conditions *almost* always occur during the eclipse phase. Top-level requirements of LEO satellite missions, however, rarely impose high power-budgets for thermal control purposes .i.e.; most LEO satellite missions employ passive thermal-control techniques to keep the system/components within the pre-determined temperature ranges. If, however, active thermal-control techniques are employed, they must be accommodated within the power-budget allocation.

Having reviewed the typical power-consuming phases of a LEO satellite mission, it must be noted that these phases, each by itself or in any combination(s), may lead to high battery DoD levels which will shorten the mission-life considerably. It is the mission designer's task to come up with mission profiles which are affordable for a given power profile/budget, thus an *adequate mission profile*. It must be noted that, as stated earlier, adequate trade-studies of the overall level-of merit of the project are *highly-delicate* activities viable only through comprehensive *technical/financial/psychological trade-studies* regarding various aspects of *satellite-service revenue, end-user needs* and etc.

2.3 Enlargement of solar array area and/or utilization of more efficient solar cells

Solar cells are extremely-expensive components used for power-generation purposes. According to [1], solar cells may be as expensive as 3000 $/W.

[6] Some especial instruments may require to be maintained at cryogenic temperatures, as low as a few tens of Kelvins. These instruments thus may impose active thermal control techniques with considerable power consumption.

2-3-1 Enlargement of solar array area

Logically, solar cells can be incorporated to a satellite structure in two ways:

1- They are mounted on the satellite exterior surface
2- They are mounted on solar arrays which are erected out of the satellite main structure

In the case of body-mounted solar cells, which is the conventional configuration for microsatellites, there must simply exist no extra surface more solar cells. If so, more efficient solar cells must be used to provide more power, if necessary. In the case of array-mounted solar cells, however, the arrays will grow inevitably larger to accommodate the extra cells. This, however, violates the structural rule of thumb: Design the arrays as small as possible to avoid downstream structural problems. Enlargement of solar arrays, may also affect the ADCS, as it may considerably increase the vehicle's moment of inertia. Thus, enlargement of solar array area must be done only via a system engineering approach considering financial, structural, control and packaging considerations.[7]

2-3-2 utilization of more efficient solar cells

Utilization of more efficient solar cells directly translates into higher cost. Thus, it remains to the project financial funding whether more efficient cells can be incorporated or not. Some of the most widely-used solar cells are presented in Table 4 [1].

	Silicon	**Gallium-Arsenide**	**Indium-Phosphide**
Planar cell theoretical efficiency	18 %	23 %	22%
Achieved efficiency	14%	18%	19%

Table 4: Performance comparison for some photovoltaic solar cells

3 Conclusion

In this paper it has been shown that the battery DoD is one of the most demanding requirements on LEO satellite missions. A system engineering approach toward the problem identifies various issues subjected to trade-studies and trade-offs to overcome the problem most efficiently. This paper presents the three alternative strategies developed by the satellite-design communities to overcome the problem:

[7] Packaging the deployable solar arrays within the LV shroud has always been a great challenge to the configuration-design community. Packaging larger solar arrays is no interesting to any configuration designer!

1- Enlargement of battery capacity and/or utilization of batteries with higher allowed DoD and/or higher power-density
2- Adapting adequate/flexible mission profile(s)
3- Enlargement of solar array area and/or utilization of more efficient solar cells

Corresponding issues of each strategy are then presented in a system engineering approach.
Which strategy to utilize and the contribution of each alternative to the final approved strategy, however, can only be fixed through system engineering studies and mission-specific trade-studies discussed in this paper.

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