System engineering approach toward the problem of required level of in-orbit autonomous-operation of a LEO microsatellite mission

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During the last few decades, identification and accommodation of the required level of in-orbit autonomous-operation of satellite missions has always been a challenging system-engineering activity for the satellite-design community. Furthermore, required level of in-orbit autonomous-operation of microsatellites in Low Earth Orbits (LEOs) is of particular interest for the space-related communities, due to the ever-increasing interest in microsatellite missions, nature of the microsatellites and characteristics of LEOs. This paper, from a system-engineering point of view, presents the mass/power-budget allocation of a typical LEO microsatellite mission and the effects of those parameters on the level of in-orbit autonomous-operation of such missions. Also, general characteristics of LEOs, which impose potential requirements and/or constraints on microsatellite projects, are studied. It has also been highlighted that identifying the required level of in-orbit autonomous-operation of a LEO microsatellite mission is an interdisciplinary activity influenced by various parameters such as mission profile, attitude control strategy, geographical distribution of ground stations, end-user

requirements and etc. Finally, it has been concluded that identifying the required level of in-orbit autonomous-operation of such missions can only be done via a system-engineering approach, considering all the corresponding parameters discussed in this paper.

1 Introduction

Highly-autonomous satellites are defined as those vehicles which require minimum contact from the external sources (Terrestrial or spaceborne) to accomplish their operations[1]. Identification and accommodation of the appropriate level of autonomy into a satellite mission has always been a challenging system-engineering activity with mutual effects on various parameters such as reliability, complexity, cost, schedule and etc. Of particular interest, however, is the Autonomous-operation of LEO microsatellite missions, due to the following considerations:

1. Nature of microsatellite missions: Microsatellites often impose stringent mass/power-budget allocations to the corresponding subsystems

2. LEO characteristics: Satellites in LEO travel around the earth in 1.5-2 hours which translates into 12-16 orbits per day[2]. Consequently, satellites in LEO *see* a given ground-station for less than 20 minutes, during an overhead pass i.e. the longest contact time during a given orbit is less than 20 minutes, followed by several orbits without any contact opportunity (for a single ground station) . These considerations must be taken into account to appropriately identify the level of required in-orbit autonomous-operation of such missions.

In the following sections, various parameters which affect the level of in-orbit autonomous-operation of a LEO microsatellite mission are studied.

2 Parameters affecting the level of required in-orbit autonomous-operation of a LEO microsatellite mission

As stated earlier, particular interest in the Autonomous-operation of LEO microsatellite missions is mainly due to the following considerations:

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[1] These operations can be divided into two mail categories:

1- Mission-specific operation such as photography of a known target, attitude/orbit-correction maneuvers, etc.

2- House-keeping activities such as thermal control, battery-status control, etc.

[2] The 1.5-2 hours orbital-period for a LEO corresponds to orbital velocities as high as 7-8 Km/s.

2.1 Nature of microsatellite missions

Microsatellites are, by definition, those vehicles which weigh between 10 and 100 kg. Experiences of the space-related missions during the last few decades have revealed that power and mass are often scarce resources for all satellite missions and microsatellites are no exception of this rule-of-thumb. Mass-budget is even more severe for microsatellites missions which are often launched as secondary or piggyback vehicles. Furthermore, there remain extra constraints on power-budget of microsatellite missions which is, in turn, due to the conventional configuration of such vehicles which is a cubic one with the solar cells mounted on the satellite's exterior facets. This configuration has been characterized as "inefficient", in terms of power-generation purposes [1]. These considerations affect the level of required in-orbit autonomous-operation of microsatellite missions in various ways. The following sections, from a system engineering point of view, discuss the preceding considerations:

2.1.1 Stringent mass-budget allocation

Mass/Power-budget allocation of the Swedish *ASTIRD* microsatellite has been shown in table 1.

Subsystem	Unit	Mass (Kg)	Power (W)	*Average power in orbit (W)*
Structure	Structure incl. solar panels	5.60	-	-
	Balance masses	1.36	-	-
Data Handling	ASTRID System Unit (ASU)	6.50	5.00	*5.00*
	Pyro unit	0.48	-	-
Radio	S-band and UHF Transmitters	0.90	16.00	*2.60*[3]
	Command receiver	0.27	3.00	*0.60*[4]
	Antennas + diplexer+ RF cables	1.58	-	-
Attitude Control	Magnetic torque coils	1.00	9.60	*1.40*
	Sun sensors	0.30	0.27	*0.27*
	Magnetometers	0.10	0.5	*0.00*
	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	-	-

[3] The average transmitter power assumes that the transmitter is "ON" 16 % of the time.

[4] The command receiver is "ON" for one minute and "OFF" for four minutes to save energy.

Payload	Energetic Neutral Particle Imager (PIPPI)	3.14	4.08	*4.08*
	Electron Spectrometer (EMIL)	0.74		
	Miniature Imaging Optics (MIO)	0.33		
	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	0.15	-	-
Total satellite		27.00	-	*21.75*
Platform		22.64	-	*9.87*
Payload		*4.36*	-	*11.88*

Table1 Mass/Power-budget allocation of the ASTRID satellite

It can already be seen that there are heavy constraints on mass-budget allocation for *O*n-*B*oard *D*ata *H*andling subsystem (OBDH), which is considered as the necessary hardware to accommodate a certain amount of software and process-capability to obtain a given level of required in orbit autonomy[5]. Logically, provision of autonomous-operation is limited by the amount of software and process-capability accommodated within a given mass-budget of OBDH subsystem. Obviously, for two units using identical hardware/software technology, the one which incorporates more hardware units (thus the heavier and bulkier one) can accommodate a higher amount of software and process-capability. This, however, remains to the system-level trade-studies whether heavier and bulkier units can be accommodated within the mission mass/volume constraints [2].

During the last 2-3 decades, however, there has been ever-increasing advancement in electronics, miniaturization of the corresponding hardware, incorporation of nanotechnology into corresponding hardware units and maturity of corresponding hardware and software. These advancements provide more autonomy-authority for a given mass-budget, in comparison with the past.

2.1.2 Stringent power-budget allocation

From table 1, it can already be seen that there exist severe power-budget and power-budget allocation (for OBDH subsystem) considerations for microsatellite missions. It must be noted that that the conventional configuration of microsatellites is a cubic one with the solar cells mounted on the vehicle's exterior facets, an inefficient configuration regarding sunlight-collection purposes Today, however, with the advancements in attitude control hardware/software and control techniques, microsatellites are 3-axis stabilized[3]. With this in mind, it is being predicted that

[5] 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.

considerably-more power will be available for microsatellite missions. A higher total amount of power available to the system-level design person/team will inevitably imply some increase in OBDH power-budget allocation. The level of power provided to the OBDH subsystem, in turn, identifies the type of OBDH software and the amount of process that can be accomplished in a given period of time. In other words, if a higher level of power is provided to the OBDH subsystem, more capable hardware-units can be incorporated, in terms of process-capability, thus obtaining higher levels of autonomy.

2.2 LEO characteristics

As stated earlier, satellites in LEO travel around the earth in periods of 1.5-2 hours and their orbital velocity is as high as 7-8 Km/s. It can be shown that for a satellite in a circular 1000 Km LEO, maximum contact time with a given ground station is less than 17 minutes, followed by several orbits with essentially no contact opportunity. Thus, if a single ground station is responsible for contact purposes[6], short and infrequent contact-patterns are imposed to the mission-design team. As an example consider a LEO microsatellite during an overhead pass over the corresponding ground station. During the pass, it may be required that a substantial amount of software/commands are uploaded to the vehicle (and accommodated within the OBDH module) to be accomplished during the time until the next contact opportunity, which may be several orbits later. To handle this challenge most efficiently and to avoid the various problems due to the inadequate contact-pattern and the downstream considerations of several successive passes with no contact opportunity, two strategies can be applied:

-Higher degree of in-orbit autonomous-operation with single/two ground station(s)

This strategy relies mostly on the satellite's OBDH subsystem to schedule and accomplish the in-orbit operations, automatically. Thus, the satellite must be equipped with enough on-board hardware, software and process-capability to accomplish the tasks by itself.[7] Furthermore, the satellite must be flexibly designed in order to be capable of repairing/updating/refreshing its software and still maintain the desired level of autonomy. On the other hand, this strategy is advantageous in terms of its low sensitivity to the number and geographical distribution of the ground stations and the downstream issues.

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[6] By the term "contact", Tracking, Telemetry and Command (TT&C) functions are mainly meant, not the downlink/uplink of mission-specific data.

[7] There must also exist numerous on-board fault detection/correction procedures available on the satellite and many other considerations needed by a system to operate automatically, with acceptable reliability. These issues, however, are not commonly discussed at system-level analysis, thus out of the scope of this paper.

- Provision of several ground stations with adequate geographical distribution and little to moderate level of autonomous-operation[8]

This strategy mostly relies on a sufficient number of ground stations with adequate geographical distribution regarding the specific mission. Logically, if the number of ground stations is increased, the contact opportunities will be more frequent (It has been assumed that the increase in the number of the ground stations is governed by the logic considering the adequate geographical distribution of the stations). Thus:

1. Fewer operations must be done before the next contact opportunity.
2. Also, housekeeping data will be downloaded to the earth more frequently and the mission-operations software/person/team will be able to uplink the appropriate commands more frequently.

The preceding considerations will directly translate into lower level of required in-orbit autonomy of the vehicle.

3 Conclusion:

In this paper, the level of required in-orbit autonomous-operation of microsatellites in LEO has been studied via a system engineering analysis. Furthermore, the two practical strategies developed by the satellite-related communities to handle the challenge most efficiently, have been discussed. It is concluded that the appropriate level of in-orbit autonomous-operation of a LEO microsatellite mission and the number of ground stations versus the level of in-orbit autonomous-operation are issues that can only be evaluated via a comprehensive system-engineering approach and performing sufficient amount of corresponding trade-studies and trade-offs regarding all the parameters discussed in this paper.

Bibliography

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[2] Wiley J.Larson and James R.Wertz., 1992, Space mission analysis and design second edition, Microcosm Inc.

[3] Triharjanto, H.R., et al,., 2004, LAPAN-TUBSAT: Micro-satellite platform for surveillance and remote sensing , 4S symposium, Paris.

[8] 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 in the scope of this paper.