# Small Satellites Constellations & Network : Architectures and Technologies.

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*Abstract :*
*Based on two constellation missions cases ( data collect and disaster monitoring by SAR radar ), the study derives architectural and related technologies required in the field of future commercial « small » onstellations. Global management from centralized control station is chosen here, with intermitent inter-plan visibility for ISL, as imposed by the low altitude and moderatly populated parameters.*

During the last four decades, the space industry encountered several mutations, sometimes concomitant : technological show case carrying strong political symbols ; scientific tools for solar system and deep space observation ; military surveillance ; meteorological complementary observations ; telecommunication.
Most of these efforts where both basically mono-satellite missions, and non or poor commercial business.

With telecommunication area, direct commercial applications appeared : life limited, costly to launch, difficult to access ; the geostationnary relay turns out to be high valuable investment for operators : customers exist, ready to pay for more TV images and more basic communications services.

Iridium , Orbcom, globalstar, Skybridge, Teledesic : the very last years space industry has witnessed great turmoil : constellation starts a new mutation.
The future of constellations can be expressed on the following basis :

- What are the services customers will be ready to pay for ?
- How is a space solution well fitted for these services ?
- Which architectures and related technologies this evolution will request ?

To drive this reflexion on a practicable way, we start with 4 concrete study cases :

- maritime surveillance mission, by eavesdropping techniques
- short-term, short-scale weather prediction and information dissemination
- disaster monitoring by SAR images
- data collect of world-wide disseminated beacons.

Of these four, the last two are retained after predefinition and market analysis.

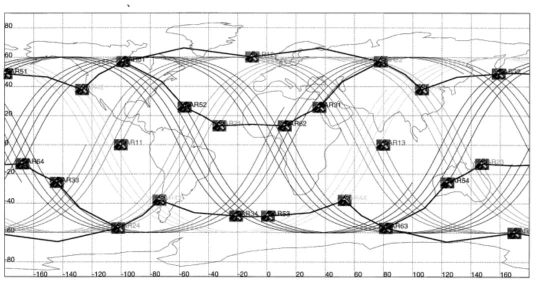
<u>Maritime surveillance :</u>
active ships radar are detected in 2_9 GHz bandwidth. The addressed market is institutional ( traffic watch in rails, law enforcement, environmental protection..) and fleet companies. A 5 to 6 hours revisit time is acquired through 24 satellites at 520 km. the payload is assessed at 100kg, including a 20 kg antenna. Power payload consumption is in the range 400W, leading to a ~ 400kg class satellite.

<u>Short-term, short scale weather information :</u>
Albeit spatial based information is the only way to provide the earth coverage inherent to the global meteorological models, there remain today a very limited share of the operational observation network. The difficulty for constellation definition is to determine the LEO sounder ( mostly water, wind and temperature) which would provide service at reasonable cost and even useful definition. Integration of the data in prediction models, and assertion of their added value arises as another huge task.
Nonetheless, less ambitious service has been predefined as follows : a fleet of a dozen of LEO clouds imagers, disseminate data to individual end-users. Ground based captors data ( wind speed, temperatures) are added. The user receives temperature, wind and cloud coverage for a local area surrounding it's immediate neighborhood. Global weather information ( from institutional regional/continental forecast) can be added.

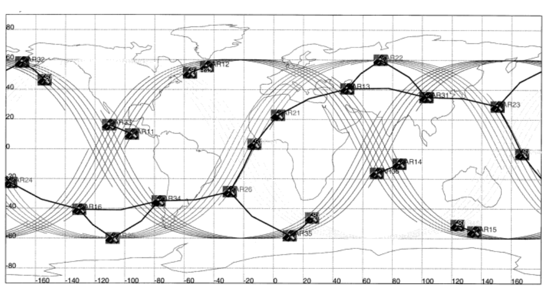
<u>Disaster monitoring by SAR images :</u>

A 2/3 m resolution is acquired through a 4*3m SAR antenna, flied at 520 km. Carrier frequency is 9 GHz. In request mode, the SAR images a ~10 km instantaneous across-track area.The beam is electronically spotted from 30° to 50° of earth incidence. Taking into account moderate duty-cycle required by the mission, coverage enhancement is assured by « virtual » dual sensor configuration, acquired through satellite reorientation ( 180° in yaw). Targeted service aims at information for institutional/commercial natural or environmental disaster crisis management staff.
A 5 to 6 hour revisit time need is identified, acquires through a 4 sat/6 planes configuration :
The definition configuration has to take into account the data retrieval process, as well as the imaging-taking orders.
A centralized command/control solution is derived, with ISL between out-of-plan satellites. Taking into account the low altitude required for radar power generation purpose, satellite inter-visibility is not continuous, and contributes to the total system service response time.
The two following figures show the typical link pattern, and it’s variation in 3 minutes.

Inter visibility links pattern.
4sat/6planes. Alt=520 km



time=t0



time=t0+3min

Data-collect mission

The system is based on a full network of worldwide disseminated beacons. Each beacon, associated to it’s dedicated sensor, measures a physical parameter ( temperature, liquid flow, trafic counter...) and emits the located and dated data toward by-passing satellite.
The system characteristics are mainly :

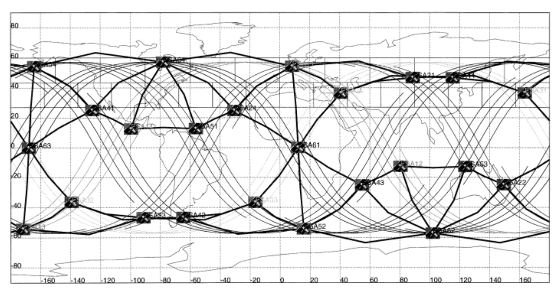
- huge number of beacons ( several ten’s of thousand in a single foot print)
- short messages (~ 128 bits )
- high diversity of services and end-users ( environmental survey, water supply and rivers watch, industrial plants instrumentation, pipe-lines, containers and truck track, urban area road trafic).

Two classes of messages can be distinguished :

- long term ( day to weeks), for majority of beacons
- short term ( few minutes) for traffic information( ~ 5% of beacons).

Traffic information beacons are CDMA coded, the message carrier is proposed at 2 GHz, targeting at low power ground beacons.
The short term mission drives the coverage needs, and result in a 900km altitude 6planes/4 sat configuration. The base-line version is composed of relay satellites, link by moderate ISL rates. A centralized command/control station is proposed, which includes the message decoding function. Data dissemination to user is performed through usual communication network.
Again, the satellite exchange strategy is driven by inter visibility links windows duration and occurrence.
There are much higher than previously, as imposed by the short time service share.

Inter visibility links pattern.
4sat/6planes. Alt=900 km



time=t0

Advanced solution is derived, where short term beacons are on-board processed.

Each satellite carries it’s on-board mission plan. Due to inhomogeneous « short term » beacons distribution, flexibility is added through information exchange between two following satellites : areas not picked-up by the first are signaled to the second.

These last two missions examples are used as an illustrative pattern for the general constellation question :

Why constellations :

Constellations are mainly driven by the following design criteria :

1. a space based function _sensor or relay_ for wide area coverage
2. an altitude limitation ( as opposed to GEO) for
   - limitation of signal power/information rate on the earth-satellite travel.
   - increase sensor resolution on ground
3. increases sensor/relays number at low altitude ( for wide coverage).

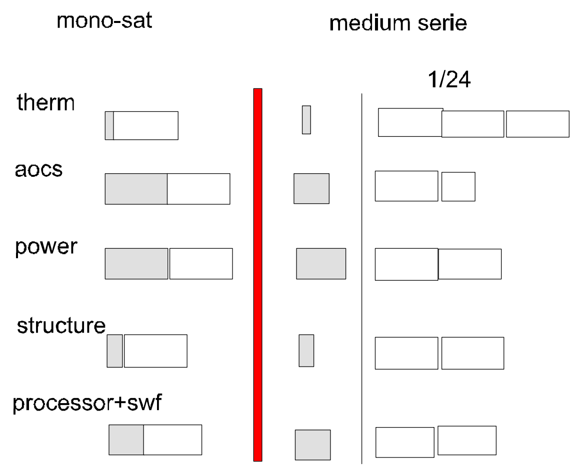
The wide area coverage criteria is fulfilled by much less numerous GEO ( or IGSO) carriers if the power limitation can be solved. The very large area earth-oriented antenna appears today possible in mid term future ( see THURAYA), at the cost of 0,2 sec signal travel time. Nonetheless, the carriers number criteria will resist to data rate and power sharing. The resolution criteria is much more resistant ( due to beam diffraction), as well as power criteria in the field of active sensors ( radar, lidar...). Here, today sensors technologies drive firmly to low altitude, and even « over futurist » geostationnary solutions appear to costly with respect to more cheaper sensors at low altitude.

<u>What is constellations :</u>
defined as multiplication of sensors/relays and associated carrier, constellation appears first as the monosatellite technologies and manufacturing processes adaptation to

1. the medium series production.
2. accommodation constraints to multiple launch ( elongated cylinders of trapozoïdal/triangular sections)

Then enlargement arises with the command/control and operation cost : many satellites to be managed simultaneously.
The 3 step is the active interaction of the constellation satellites, sharing functions and exchanging data.

Accommodation of mono-satellite technologies, possible distribution of platform functions.
To assess the interest of whatever new technological accommodation, and classification of their relative wieght, we need a first rough economical scale. We first sketch a classification of platform sub-system according to the following. Starting from the usual relative cost of the platform subsystem ( as known from mono-satellite common design), with evaluation of both recurrent ( design analysises, hardware cost sharing) and non-recurrent ( hardware and integration), we distribute it in the context of small series production. This first evaluation has then to be completed by possible lever effect of considered technological field on the others.
Of cause, economical environment is strongly difficult to generalized, but we proposed to keep in mind a distribution as follows:
(where bolded area for non recurrent parts, white for recurrent ones) :




The mono-sat case is intended as based on common standard small observation satellite ; where standardization on each chain is already high, as is largely the case today.
The medium size serie exhibits a reduction of equipments cost. Most chains design effort is enlarged ( by several times), as optimization effort as well as redefinition and inherent loop processes can be expected larger for the more complex constellation mission.

**Attitude & Orbit Control & Determination :**
Attitude control of many satellite is first thought as the same as for mono-satellite case. As this function is consuming in electronic sensors & process, the evolution way can be foreseen in direction of

1. power reduction ( with lever effect on power sources sizing)
2. internal bus and sensor interface standardization.

In addition to these S/C technologies, our two missions examples lead to the following axes identification ::

1. control of optical ISL terminal, with great orientation accuracy( few micro-rads), on platform that other mission needs design as much less requiring (ten times at least) in attitude control. Double stage loop AOCS, with closed loop (between emitting and receiving satellite) beam orientation is identified.
2. for any emitter, knowledge of each sat position to determine first rough pointing

3. For observation with medium duty-cycle (- « take image on request), revisit time is increased by sensor reorientation. In case of large inertia/high dynamic involved, reduction of TC bandwidth is worth (as accurate pointing requires then numerous elementary TC ).

On more general basis, the distribution of attitude and orbit determination functions can be sketched as followed :
Obit determination can be achieved by taking advantage of constellation architecture :

- inter satellite ranging, for ISL equipped constellation, gives relative inter-sat distances, on the « constellation sphere ».
- a référence position of the mesh is then regularly acquired by centralized center Doppler measurement of « the sat in visibility ».

Attitude determination distribution can be achieved like in « GPS like attitude control » : phase shift of the same plan wave signal received in different part of the satellite gives orientation of the receiving base with respect to signal traveling direction. Accuracy, decreasing with vawe length and strongly affected by reflection noise has to be revisited in the context of high RF ( several ten's of GHz) ISL signals.
A second, but non-interferometric way, is possible in case of OISL. High accuracy measure of the turret beam orientation with respect to emitting S/C frame, associated to inherent small divergence of the « fine » optical beam and realistic knowledge of both S/C absolute positions, leads to fairly accurate attitude knowledge at small extra cost.  ( Coarse attitude sensor remain mandatory _ S/C safe mode ; acquisition at constellation deployment).

**Thermal :**
The simplest thermal hardware ( fixed radiative area sized on warm case conditions, and compensated by on/off regulation of fixed power heaters) is the most popularized. The non recurrent cost is very low and the lever effect is potentially high as external radiative area required impacts size of S/C body and cold case external flux impacts power source sizing.
Then essential in the cost is analysises, aiming at refraining potential over-sizing.
This analyze effort is impacted by

- significant variation of
    - external earth flux.
    - sun elevation on orbital plan.

Both conditions commonly encountered in LEO constellations, where earth flux is high and satellite plan is sun-drifting.

- multi-launch design, which drives to « exotic » compact shapes

In addition, increase of on-board processing, impacts internal dissipation stronger than external available area, which rises new needs for thermal power dissipation.
Then, possible evolution will be increase of more active control hardware :

- variable conductance heat-pipes, with associated deployable radiator
- area of electrically control emissivity (loovers or electrically controlled emittance materials).

which allow more dissipation efficiency for the same volume, and adapt with only low power need to strong internal dissipation changes.

**Power generation :**
As soon as power generation is implemented on each single satellite, evolution in constellation will follow the mono-satellite technologies ( with battery mass capacity ratio decrease), and, more significant, strengthened improvement of solar array efficiency needs, due to more accommodation constraints, in the multiple launch context. (our SAR mission example, a sizing at 3' duty cycle for the 3,5 kW/200W payload requirements, leads to a 10 m2 AsGa SA ).
When dealing with « how to take advantage of the constellation architecture to share the power generation function », even futuristic design seem to be rejected for next two decades. Any way, in today design, power generation in the constellation is already fairly well distributed, where each satellite is a power collector/converting node. Next step, where satellite in sun can collect and transmit power to sat in eclipse (or in « extra power need » state), would be favored by the relative higher ratio of « maximum eclipse duration/orbital period » wrt « shadow part of sphere / illuminated part of sphere ». Which gives way for efficiency required smaller for the global chain ( primary collector, converter, transmission by relay jumps, distribution..) than for the chemical (or mechanical) storage chain. Nonetheless, this required efficiency remains 0,81 (at best) of those of the classical chain at 600 km, and 0,67 (at best) at 1500km. Then, diffraction losses on the transmitted beam kills any tentative.

**On-board software and ground command control**
The frontier between on-board and ground software in any satellite application is :

- the time lapse of the chain « TM/TC signal travel & human analysis and decision time » ( strong impact on AOCS & FDIR)
- the criticality, which push on board strong reliable automatisms ( ex : stop the battery on excess temperature..)
- the expected skill of operators team

- the reuse of existing ground station
- the historical separation between ground and on-board software team within an organization (both team do not share the same tools and development processes )

With constellation, this frontier moves, as most of these factors are affected.

FDIR :

FDIR starts first from mission availability requirements. Considering satellite technology, FDIR implementation can be then sketched as follows : if availability is low, the first simple implementation is to cut off payload if anything wrong with it, to go to sun-pointed safe mode if anything wrong with platform. Then, when availability requirement increases, transition to safe mode is delayed by recovering of low critical functions failures without impacting higher level. With the constellation mission, availability can be reassessed because :

- many satellites leads to many mission carriers, on which mission can partially be redistributed,
- observability of each satellite, if enhanced, will allow preventive actions for this redistribution.

Availability distribution :

SAR example :

In the SAR mission, each carrier is an imager, and the central sequence of the mission can be so derived :

1. a request for a desired earth area to target is issued from the central station
2. a SAR over-passing the area will further takes the image
3. the image is delivered to the station.

(in our solution, the transfer from ground to imaging SAR travels through the constellation, by ISL).

Then, considering the second step as it's final goal, the first step is decomposed as follows :

- identify the first carrier above the station( which will establish « station-constellation » link)
- identify an imaging SAR
- identify the path through the constellation
- ask for instruction if time is delayed)

If all steps are performed on ground, prior to command loading ; then any unavailability events in the constellation ( relay carrier, end-chain imager..) fails the sequence.

According to overall mission need ( takes image in crisis situation), the probability is almost certain that image remains required, and a new sequence for the same goal ( takes image of the same area) has to be redefined and reloaded. Again, this redefinition will be performed with the delayed knowledge of global « constellation health-status ». On board implementation strategy is then worth, considering

- the information travel time in the constellation : each relay node knows it's neighbors' health statuses sooner than the centralized station
- mission time lost with time for redefinition is non linear ; and real-time redirection of the final goal ( end imager satellite) to the neighbor next one, can save significant delay.

Data collect example :

Here, both revisit time and window visibility gaps between satellites are much shorter. But good design leads to affect these lapses to the total service time. Then, any failure vent which aborts the planned pick-up of an high rate beacon area need short time recovery. On such event, on-board recovery action is worth, where the active satellite involved pass the missed area identification to the following, which modify it's own plan. The picking function is then redistributed on-board according to the sequence :

1. failure event and missed beacon area detected by node 1
2. neighboring nodes identification by node 1
3. failure information transferred to node (i)
4. redefinition of picking plan at node (i).

Here, potential saved delay is 200%_300% of the service time.

In both cases, mission availability is significantly increased by real time redistribution, through on-board strategy.

The cost in processing load is here :

- redistribution strategy algorithms
- on-board generation, at end node, of the full set of low level command sequence ( high level instruction : « takes SAR image » or « pick this area » at that time, has to be split on-board in each elementary action of sensor activation, beam orientation resolution and timing ).

When brutal force algorithms can be used here for these processing, more flexibility [ with goal driven plan generation and event driven redirection algorithmic] would be useful. When event tree explodes, testing and development consideration makes it mandatory.

This will then push to on-board interpreter, or some mixed compiled/interpreted solution.

Preventive action :

In usual FDIR, recovery action is performed at failure occurrence, by elementary action : internal measure on a component is outside a predefined set of value( binary for switch position ; array or table

for configuration vector ; threshold limits for analog parameters...).
These measure points are also the satellite telemetry points, and their analysis is deferred to ground for further mission reconfiguration.
With increasing satellites number and increasing S/C internal software complexity ; the need for preventive information on the system arises. This can be realized through internal auto-tests, on non active functional chains or equipments :
A test mode is defined at equipment level, ( equipment ON but isolated from active function), a set of logical values is successively injected in input of the component, dedicated outputs are recovered and stored for ground send.
With this additional testing effort, possible impasse in the reconfiguration tree can be pre-identified.

Operator control function :
In our two missions example, we choose to command each satellite by traveling command through the constellation with ISL. In both cases, the traveling paths are highly impacted by inter-satellite visibility, due to moderate number of satellites and their low altitude.
Albeit TC rate ( 4 kbs ) is here low with respect to retrieval data rate, the need for advanced on-board software ( like path determination algorithms, on board command generation, recovery strategy and new mission plan update) leads to new generation facilities for software and file up-loading.
As viewed from ground, the low level implementation of any compiled code is cumbersome to handle ( where data addresses of any variable or on-board routine are to be known for each satellite, and exactly included in any upload ). In addition, full low level description of code will use significant bandwidth.
Again, the general need can be identified for on board interpreter solution.
The specific development of spatial solution can be the way, but hardening (by example restriction of functionality..) of existing broadly used solutions ( like JAVA), has been identified as potential future way in this study : it offers the advantage of numerously tested and debugged software, which could be main driver in this context.

Ground center :
In high real time commercial services, the high level of availability required, as well as the over-all system cost has driven to permanent human watch. The same constraint holds yet for constellation, where in addition the number of satellites per human operator increases ; to increase then human efficiency, higher level interface are needed for system observation and for command generation.
command

- command generation from high level order ( with integration of associated simulation test tools )

observation :

- telemetries filtering and gathering
- automatic alarm thresholds, reconfigured according to the mission
- failures diagnosis and interpretation

For these advanced observation tools, rules-based non deterministic system are apparently poor in real-time high reliability context, but real time model-based system can be derived :
a model of the satellite is run on ground which includes external environment ( orbit, sun fluxes...) and operator actions ( TC) ; expected evolution is simulated and resulting « telemetry flow » is compared continuously to satellite real-time telemetry flow. Then, at discrepancy, warning and diagnosis are issued for operator.
Today on-ground implementation on geostationnary telecommunication satellite (ex : TURKSAT) shows that system remains well within the processing performance of a COTS work-station.
For constellation, direct translation leads to solve the question of « as many ground models that satellites », with the additional constraint of non-visibility gaps.
Temptation will then be high to transfer the function on-board with by example partial implementation spotted on critical functional chains.

Conclusion :
Derived from two medium size and low altitude missions, our study has illustrated some more general architectural requirements for constellations ; the enhancement of ground observation tools , accompanied by more on-board autonomy will increase the human ability to control the system. With the use of ISL technologies, constellation can be understood as cooperative set of agents, where mission is enhanced by redistribution. Real time on-board redistribution gives a way for more availability performance.
The development of reliable interpreter language seems a way for the highest software flexibility required, both for ground control optimization and data & code files transfer into the constellation.