Romulus: Along Track Formation of Radar satellites for MTI (Moving Target Identification) and High SAR performance

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Abstract: **The concept implements the coherent combination of an along track formation of typically 4 SAR satellites spaced by few meters. Formation Flying is shown to extend the usual space borne capabilities: MTI (STAP technique) with 2 m/s minimum detectable radial velocity and high performance SAR (SAR Train technique) with 0,5 to 1,5 m resolution up to very high incidence (70°). Two formations on a same orbit plane provide a 12 hours revisit. Reflect array antenna technology combined with satellite attitude agility allow up to five data takes (10 km x 10 km scenes) on theatre of 300 to 500 km sizes. Very High SAR resolution SAR (0,3 meter) is also provided. Romulus is part of the joint CNES/ONERA programme that covers all the formation flying research and advanced project studies whatever the application area, astronomy, observation.**

I BACKGROUND AND OBJECTIVES

For several years, a research program of ONERA has studied the Radar capabilities of along track radar formations for Moving Target Identification (MTI) and developing the corresponding algorithms, particularly around STAP. On its side, CNES has developed an expertise and pioneered the SAR formation flying through the detailed studies of the now well-known Cartwheel concept. CNES has also performed studies on small X band SAR satellites (< 200-300 Kg) and related technologies (reflect arrays) able to be flown in formation together with the development of specific along track formation flying techniques like the SAR train that dilute the antenna area and power requirements on N smaller satellites to reach high SAR image performances. Based on these previous research and technology activities, the Joint CNES ONERA Romulus study aims at defining and optimising a future mission for MTI and high SAR performance for military and civilian surveillance. The study is performed within PASO (Plateau d'Architecture des Systèmes Orbitaux), the CNES organisation in charge of pre-feasibility studies.

This study is "technology oriented" since it aims at addressing the capabilities of SAR formation flying techniques with respect to potential future needs rather than to answer to formal requirements from Defense or Civilian Security authorities. Nevertheless, the driving user needs for a system providing SAR and MTI can be easily anticipated.

II NEED DRIVERS

A *SAR and MTI data in X band*

The needs are focused on terrestrial theatres of typically 500 Km, either civilian (catastrophes, surveys) or military. Two kinds of data are required: SAR only with Very High Resolution (< 0,5m), MTI data combined with moderated SAR images (< 2 m), with respective scenes sizes of at least 5 km and 10 km. The radial speed detection threshold must be as small as possible, at least < 2 m/s. The system should detect target with RCS greater than 10 m² with an elementary (before the tracking gain) probability of 0,9. SAR noise Neσ^0 should be better than 19dBm²/m². For maritime applications, the minimum RCS is increased by 10, like the resolution and images sizes requirement: Scansar mode is required. SAR data and particularly MTI need to be associated with high revisiting performance, at least better than 12 hours.

B *Operational requirement: coverage, production capability,*

3 to 5 scenes must be taken on each theatre overpass and 2 to 5 theatres must be covered on each orbit. Polar cups coverage is not mandatory and local time variation is welcome. The MTI technique is based on the radial (along the line of sight) radar velocity, to increase the MTI detection capacity it is therefore necessary to multiply the MTI takes of a given scene with different azimuth angles, multiplying the MTI takes is also necessary for short term target motion tracking and better identification. Figure 1 illustrates a typical sequence of MTI +SAR data takes and the need for high steering agility that can be achieved by electronic antennas or satellite manoeuvres or a combination of both.

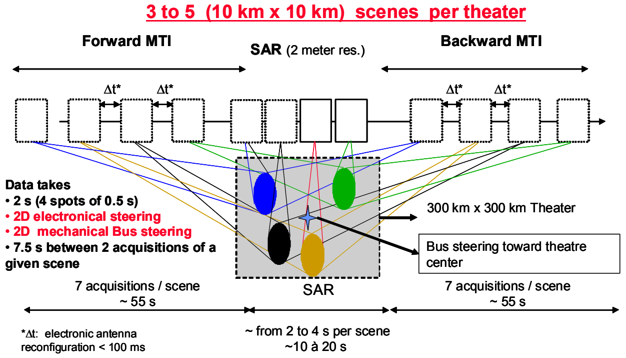

Figure 1 : Typical sequence of MTI and SAR data takes

III TECHNICAL DRIVERS AND TRADE-OFFS

A *Preferred antenna formation geometries for MTI*

A moving target and a ground clutter that are seen by the Radar with a same Doppler are not seen along the same azimuth angle. The deviation is function of the radial velocity of the target. A multi-array antenna that enables a flexible azimuth pattern can suppress the clutter while keeping intact the target signal, and can therefore detect and localise moving target even hidden under the clutter. This is implemented on adaptive way according to a STAP technique[1,5]. Longer is the antenna, steeper is the nulling and lower is the velocity threshold. This MTI technique is well-known in airborne SAR but much more difficult in space because the antenna must be much longer. An along track formation of N antennas allows the construction of such long antenna, gaps between antennas increase the total length at price of some performance degradation due to the gap factor. As shown by Figure 2, several formations geometries of different total length and gap factors are compared under the criteria of minimum detectable velocity, velocity ambiguity rejection and target localization performance. As explained later, antenna technology constraints are also considered for establishing the preferred formation indicated in the Figure 2.

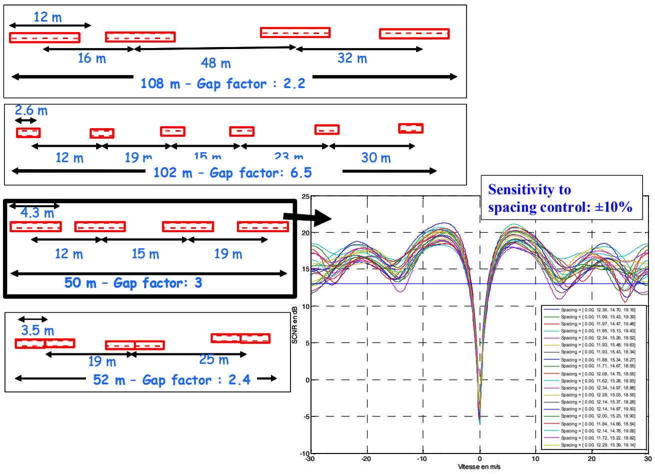

Figure 2 : Considered MTI antenna configurations and sensitivity to the antenna spacing control accuracy

B SAR TRAIN techniques for SAR performances extensions

According to a possible implementation of the SAR TRAIN concept [2, 3], N antennas are placed along the track, only one transmits and the N antennas receive the echoes. There are two modes for the coherent combination of the N echoes. The Signal Summing mode (SS SAR Train) adds coherently the results of the N synthetic antennas for a benefit of N on both the noise and the ambiguity ratios. This mode supposes only a random spacing of the antennas at the scale of twice the sampling interval V/PRF (modulo twice the sampling interval), that is to say a random spacing at the scale of antenna length (modulo the antenna length). The Antenna Dilution mode (AD SAR Train) provides an interleaving of the sampling of the N synthetic antennas and therefore enables a reduction by N of the PRF for an equal real antenna length. The elementary antenna height can be therefore reduced by N (in other words: the required single SAR antenna area is diluted over N smaller bodies) and the swath increased by N for equal ambiguity ratio and equal incidence. Another way to see the interest is to keep the original single SAR antenna height and to extend the maximum incidence up to the point that should require an antenna height N time greater in monostatic SAR to keep the same ambiguity ratio. The SNR is either increased or decreased by N whether we compare to the monostatic SAR with small or with large antenna height. This is illustrated by Figure 3 for N= 2.

In SAR, the antenna area is primarily driven by the ambiguity constraint at the desired high incidence limit where the swath is generally locked within the 1 db aperture of the narrowest available antenna beam. With the antenna (2,1 m x 4,3 m) retained for the reference scenario, the usual incidence limit should be around 62° for a swath of 20 Km at 600 Km altitude. AD SAR Train extends this limit up to 71° using the same narrowest beam, with a swath that progressively goes up to 40 km and a SNR at 71° that is roughly the same than the one obtained at 62° in monostatic SAR. AD SAR Train can be also used under the first high incidence limit with the purpose to widen the swath beyond the usual ambiguity constraint but, if we want to preserve the SNR, the swath extension must be limited to $N^{0,5}$ (Two ways antenna gain loss just compensated by the N coherent reception summing). If we prefer to improve SNR by 6dB or improve range resolution by 4 at equal SNR, it is easier to implement SS Train and to reserve AD Train to the key purpose of high incidence extension and revisit improvement at moderate resolution.

AD Train is more difficult to implement than SS train since it requires a regular spacing of the antennas equal to 2V/(N * PRF) (modulo 2V/PRF) according to a very good accuracy. [2, 3] proposes the use of spread spectrum to remove the need for regular spacing while [4] proposes to keep std wave form and to relax the regular spacing accuracy with reconstruction algorithms, at price of other constraints (SNR loss, PRF constraints in case of formation flying antennas). However more work is needed for both approaches. As shown by [2,3], with N=2, the things are made easier since we can synchronise the PRF of the transmitter so as to have the distance with the other antenna equal to an odd factor of V/PRF. Any of the considered MTI antenna formations offers, depending on the selected antenna pair and the selected odd factor, around 10 discrete possible PRF values with deviation between -25 % and 25% with respect to the theoretical sampling PRF = L/V. Such PRF variability enables the SAR timing. Indeed, with an antenna length of 4 m, a swath of 10 km occupies less than 25 % of the timing diagram (in std SAR above 50 ° incidence), i.e. less than 12 % in AD SAR train with N=2. Assuming that 16 % of the timing is also taken by the transmit time (8 % duty cycle) and the range echo correlation edge, that lets more than 70 % of the timing freedom. Any particular PRF gives 2 chances over 3 to work properly (1 over 2 with 20 km swath).

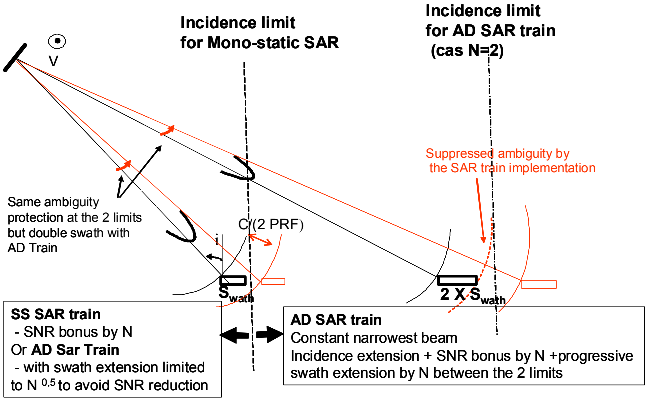

Figure 3 : SAR Train for Incidence extension (case N=2)

For this particular MTI + SAR mission, the interest of a full AD SAR train with 4 antennas may be questionable since 70° is already a high value for incidence limit and to reduce the total antenna area (for same incidence limit) would conflict with the MTI SNR. Moreover, the regular antenna spacing (with reconstruction algorithm approach) is not a good geometry for MTI.

C Formation Control and knowledge requirements

The SAR train formation constraints are detailed in [2, 3]. For both MTI and SAR Train, the antenna must fly along the same trajectory (within an earth frame). MTI along track control must be better than 10% of the antenna separation. Figure 2 shows that such error has no impact: the STAP filter pattern offers a “plateau” that is still above the moving target detection threshold of 13 dB. Because of flight dynamic laws, such along track requirement on such short along track formation naturally enables a tube width performance better than 1 meter, which is well better than the typical SAR train requirement (100 m) given in [2, 3]. This practically removes the constraints of terrain knowledge accuracy (required for correction of the phase deviations due to the antenna separation orthogonal to the radar line of sight) and of maximum terrain smoothness (to keep the efficiency of ambiguity nulling).

The MTI formation knowledge requirement is around few cm (along and across track) and few mm along the radial direction (Radar line of sight). SAR Train knowledge [2, 3] requirement is similar. In both cases, this knowledge is necessary only for the signal processing which can be done on ground. The AD SAR Train PRF synchronization needs real time knowledge of few cm.

D *Metrology, Control, collision avoidance*

On such short distances, differential GPS can provide the "cm" relative knowledge for the non radial directions, and in real time for what is required for PRF synchronization. The mm relative knowledge along the radial direction, although not real time, is more challenging. Moreover it includes also the relative clock knowledge between antenna systems that is not measurable by DGPS. This radial requirement is better achieved by the comparisons of the phase of the SAR data received from each antenna on same pixels, after correction of phase deviations due to antenna separations on the non-radial directions. This radial measurement requires only low resolution SAR data that is available from both the normal SAR and the MTI Romulus data takes. The formation control quality is driven by the differential perturbations, the thruster accuracy and real time relative localisation accuracy. The main differential perturbation comes from atmospheric drag, especially in a case where a satellite can partially mask the drag to the follower. There is no yet measurement data of such phenomena, its impact is also proportional to the atmospheric density that is non constant or not well-known. However simulations show that cold gas thruster enables 10 cm control accuracy with hypothesis on masking varying between 3 and 30 % and with atmospheric pressure variations over a 1 to 10 range (above the 2.3 10^{-12} kg/m^3 that corresponds already to a worst case with 600 Km altitude and high solar activity period) at the orbit scale. The phenomena uncertainty (masking and solar pressure) impacts the ΔV budget rather than the control capability. In term of ΔV budget, it appears preferable to almost close the relative altitude window (few cm) even if the spacing control accuracy is consequently brought down to 10 cm instead of 1m required. Mean hypothesis over the satellite life time of 10 years leads, for a satellite of 250 kg, to a ΔV of 2.2 m/s per year and a cold gas mass of 8 kg (same ΔV is considered for scenario using more massy satellite although ΔV should be lower). The thrust sequences can be sufficiently separated to allow data takes without thrust perturbations. Further studies will check the possibility to replace cold gas thrusters by more efficient hydrazine thrusters. The latter are anyway necessary for the fast extension of satellite separation in case of any satellite troubleshooting that may jeopardize the minimal functions required to avoid collision. This is done by a geocentric thrust of 30 cm/s that eject a satellite from the formation by a hoping over the others and a second reverse thrust that stabilizes the satellite 1km away on the orbit. After failure detection and recovery, the satellite can be brought back into the formation by the same hoping. The hydrazine budget considers 5 formations breaking and recovery per satellite during the life time.

E *Radar Payload technology (antenna, TWTA)*

Active antenna technology has been discarded because of cost and weight handicap, especially in such case of a formation of satellites. On the other hand, the remaining antenna options, parabolic or reflect array, are dependent from the availability of the TWTA technology critical to develop and qualify. We consider the SARlupe 6 KW TWTA (with 8% duty cycle) and the possibility to have two tubes in parallel. Antenna length is fixed through the MTI along track antenna configurations while antenna height is driven by the MTI SNR in relation with altitude and the high incidence limit. The parabolic option is the lightest and cheapest one but it cannot fit too elongated antenna shapes. Moreover, the steering agility over the theatre is limited (less number of scenes in the theatre) since it relies only on satellite attitude maneuver. SAR spotlight is possible, but not Scansar, which eliminates most of the maritime applications. In spite of extra losses (3 dB) reflect array is well indicated since it enables beam shaping and 2 D electronic steering. Nevertheless electronic steering angle is inherently limited by the gain loss (affects mainly MTI) and the range resolution/bandwidth (affects mainly SAR although the steering requirement is less than for MTI – see Figure 1). This is why a minimum satellite steering toward the theatre center is still necessary. In High resolution SAR mode (0,5 meter, up to 600 MHz), the satellite steering is even required between the scenes. The performance analysis are based on current Reflect array R/T study and breadboarding made by Thales using MEMS technology for the phase shifters. The MTI SNR requirement at highest incidence 70° and 600 km altitude leads to a 4,3 m x 2.1 m antenna.

F *Orbit, altitude; incidence range, revisit, number of formations*

The satellites are able to switch between left are right side of the track by attitude maneuver. The low incidence limit is 20 ° for SAR. For MTI it is better to increase this limit up to 27° or 28° to improve the geometry for ground velocity detection. Getting a revisit time of 12 hours (> 95 % of the world) with only two formations requires a maximum incidence of 70° at 600 km altitude. The two formations are separated by about 110 ° and fly on a near polar orbit. As said, the high incidence limit is driven by the radar distance and the link budget and not by ambiguity and the antenna area, thanks to the AD train implementation for SAR. For the same maximum distance (1400 km), lower altitude can provide slightly better revisit with higher maximum incidence range, which is good for MTI geometry but brings operational limitations from relief shadowing and moreover increases the atmospheric perturbations on the formation control. A higher altitude brings no revisit advantage but offers an extended revisit capability for SAR with degraded SNR since the high incidence limits are 62° and 68° respectively for the radar distance (SNR) and the ambiguity constraint while the two limits are much closer at 600 km.

G *Satellites and launchers*

All the satellites of a formation are identical and transmit/receive, although only one transmits at a given time. The approach with a single T/R satellite and several Receive only satellite would save, for the receive satellites, the TWTA and the energy resources (solar array and batteries), but nothing related to the radar antenna and the telemetry. With only T/R satellites, the same overall energy resource can be shared over the four bodies since the transmit burden can be moved between satellites along the orbit from a theatre to another, the formation offers a greater system redundancy (especially against TWTA failures) and there is a single development cost. Moreover, it is paramount for the formation control to have satellite of equal S/M (along speed cross section over mass ratio).

Although this preliminary study did not allow a thorough design of the satellite, the mass of the satellite (2 TWTA and 4,3 x 2,1 reflect array antenna) can be estimated in the range 600 to 800 kg. Table 1 gives some key figures. The main drivers are the acquisition time per orbit (3 minutes), the attitude agility required over the theatre, and also the 10 years life time that is achieved by redundancy of the critical items (except the TWTA that is redounded at the formation level).

Satellite requirement	
Life time	10 years
local time	variable
Transmit duration per orbit	3 minutes
attitude agility (reaction wheels)	2 degres/sec
Payload	
antenna size / mass (with deployable feeder)	4. 3 x 2.1 / 100 kg
2 TWTA	50 kg
Payload mass / power	**200 to 250 Kg , 130 W**
Bus	
Solar array	3 M^2
Hydrazine for station keeping and collision avoidance	33 kg
Cold gaz formation control	26 Kg
Bus mass	**~400 to 450 Kg**
TOTAL satellite mass	**~ 600 to 800 Kg**

Table 1: Satellite key figures

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Two SOYOUZ launches (from Kourou launch pad) enable the deployment of the two formations. The replacement of the satellites can then be done by VEGA on a 2 by 2 base. When a satellite fails, the second satellite of the VEGA launch is placed on spare somewhere in the orbit plane.

IV PERFORMANCES AND ALTERNATE SCENARIOS

A Performances

The reference scenario considers 2 formations of 4 satellites at 600 km, each satellite carrying 2 TWTA and a 4,3 m x 2,1 m Reflect array antenna. Key performances are summarized by the table 2.

SAR + MTI Operationnal Performances

Theater size: 300 to 500 km	3 to 5 Scenes /theater	5 theaters /orbit	Theater separation > 500 km	

MTI

10 Km x 10 km Scenes, 27° to 70 ° incidence, 12 H max revisit
Radial velocity detection: > 2 m/s (for SER > 10 m^2)
Ground velocity detection: 4 to 8m/s for velocity angle w.r.t. ground track > 30°, 3 to 5 m/s if > 50°
Target localisation : < 50 meters
Case of maritime target: Radial velocity > 6 m/s (> 1m/s) with SER

SAR with SS Train < 62° incid. and AD Train > 62°, Ne0 > -19 dBm2/m2

	Resolution	Swath	Incidence	max revisit interv.
Strip map (with MTI)	2 x 1,5	10 km	27° to 70°	12 H (95%)
Extended Strip map	2 X 1,5	10 km	20° to 70°	< 12 H
Spotlight HR	0,5 x 0,5	10 km	20° to 62°	12H (95%)
Spotlight VHR	0,3 x 0,3	5 km	34° to 59°	< 48 h
Scansar		200 km	20° to 70°	< 12 H

Table 2: Key performances

The worldwide revisit performance of 12 hours provided by the SAR + MTI mode (27° to 70° incid.) is also achieved (95% coverage) by the high resolution (0,5 meter) SS train SAR mode (20° to 62°). The latter is driven by ambiguity (2 dB margin on power at 62°)

B Alternate scenarios

Single TWTA: 2,5 dB less on transmit power leads to reduce the maximum radar distance by 1,2 and the high incidence limit for the SAR + MTI mode is now 63°. The revisit is still 12 Hours provided that the low incidence is 20° instead of 27° or 28°, which corresponds to a degradation of minimum ground velocity. The revisit in high resolution SAR is degraded too.

Single TWTA, smaller antenna (4,1 x 1,3 m) , smaller satellite: The SAR + MTI mode works only from 20° to 60°, which gives a 12 h revisit only for 85% of the coverage, provided that the MTI scene is reduced (at least at high incidence) down to 5 km x 5 km and the SAR range resolution down to 3 meters. This scenario can be achieved with satellites much smaller (around 350 kg).

V CONCLUSIONS AND FURTHER WORKS

Rather than a thorough feasibility analysis, this preliminary study aimed at demonstrating the potential of Formation flying in Radar and identifying the key technical points that need and deserve further investigations. Formation flying enables an unique MTI capability in space and in same times, without extra cost, a SAR capability that is very difficult to achieve in monostatic SAR. Indeed, a monostatic SAR would require 2 times higher antenna and 3 dB more power for covering all the SAR modes or would require 4 times more transmit power (48 Kw !) but without providing the high incidence SAR combined with MTI.

Further investigations should be performed in several areas:

- Use of AD SAR Train with 4 satellites (reconstruction algorithm or new waveforms), possibly combined with higher altitude and therefore better revisit.
- Formation Radial metrology over sea (SAR calibration may not possible on sea images)
- Necessity of clock synchronisation (bistatic SAR)
- Duty cycle extension to bypass SNR limitations with a single TWTA, in conjunction with synthetic bandwidth, nadir echo nulling.
- Thorough comparison of STAP and ATI techniques for SAR, in particular with the purpose to bring down to 3 or 2 satellites per formation.
- …

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