CGMS-48 EUM-WP-04
V1A, 14 May 2020

Prepared by EUMETSAT
Agenda Item: 7.1
Discussed in WG-I

Coordination of LEO orbits – Outcome of Simulations

In response to CGMS action/recommendation WG1/7.1 A47.10
HLPP reference: N/A

Executive summary:
To maximise the amount of instrument observation collected with the most efficient use of ground station resources, it is beneficial to reduce pass scheduling conflicts through the coordination of the orbital phasing of satellites within and between satellite operating agencies.

A preliminary analysis was provided in paper CGMS-47-EUM-WP-09 which demonstrated the potential benefits of in-orbit coordination, identifying the main drivers and constraints in achieving that goal.

This paper is in response to the Action A47.10 to perform a more detailed analysis consisting of:

- developing a simulation algorithm considering all identified variables impacting the LEO orbit coordination,
- developing plots and other simulation outputs as tools for illustrating the potential coordination possibilities and improvements in both global and direct broadcast mission return.

The goal of the output of Action A47.10 is to form the basis of a Best Practice on coordination of LEO orbits (Action A47.11).

This paper reports on a prototype simulation algorithm which has been built for assessing in-orbit coordination possibilities and benefits. This can be applied both for future, to be defined missions and for specific, currently defined or operational missions.

The paper recommends that further work should also be performed on the prototype algorithm to provide analysis results for optimising orbital configurations to avoid radio frequency interferences between satellite system operating on multiple orbital planes, where more than one antenna is available at a specific ground station site.

The simulation outputs are also currently rudimentary and should be developed further once the full functional scope of the tool has been defined.

It is therefore recommended that this work be performed prior to the formulation of the foreseen Best Practice.

Action/Recommendation proposed

Recommendation on A47.10: It is recommended that the simulation algorithm and outputs presented in this Paper are reviewed by CGMS Member experts in mission analysis to:

- ascertain the applicability to operational and planned missions
- determine further work required on the prototype simulation tool.
- assess its role in the formulation of a Best Practice on coordination of LEO orbits (Action A47.11).

CGMS-48 EUM-WP-04
V1A, 14 May 2020

Coordination of LEO orbits – Outcome of Simulations

1 INTRODUCTION

1.1 Objective and Context

The topic of Orbital Phasing was first introduced in the Direct Broadcast Best Practices at CGMS-44 in 2016 and has been presented at all subsequent meetings. The expected benefits have been identified as follows:

- Reducing pass scheduling conflicts
- Maximising the amount of instrument observation collected
- Reducing risk of radio frequency interference
- Fixed temporal separation between instrument observation
- Reduced risk of satellite proximity

In-orbit phasing within same orbital plane / operating agency already occurs, as presented to CGMS-46[1], demonstrating the ease and benefits of this coordination.

Further to this, a preliminary analysis of the drivers and constraints in coordinating LEO satellite orbits and the potential gains in terms of improved mission return and ground resource usage efficiency was presented at CGMS 47[2].

Building on these previous inputs, this paper provides a more detailed analysis. In particular:

- a prototype simulation algorithm is defined for different constellations and satellites in each constellation;
- Scheduling conflict statistics from anywhere on Earth are shown for any in-orbit phasing separation and for any different orbital plane separations;
- Based on use cases, improved illustrations of the coordination possibilities for in-orbit separation between different satellites and satellite constellations / operating agencies are provided.

This can then be used to determine the potential benefits of in-orbit coordination and for ultimately deriving, along with previous analyses, the recommendation for the formulation of a Best Practice.

1.2 Document Structure

Section 2 overviews the outcome of the preliminary analysis of the LEO Orbit Coordination provided to CGMS-47 [RD.2].

---

[1] CGMS-46-EUM-WP-15: Update of CGMS agency best practices in support to local and regional processing of LEO direct broadcast data. [RD.1]

[2] CGMS-47-EUM-WP-09: Coordination of LEO orbits – An analysis [RD.2]

Section 3 introduces the simulation algorithms identified along with the results obtained after their implementation. These include plots and other simulation outputs for illustrating the problem and potential benefits of in-orbit coordination.

Section 4 presents dedicated use case examples for Global and Direct Broadcast data acquisition, as well as addressing the application to Radio Frequency Interference coordination.

Section 5 summarises the work done in this and previous papers addressing LEO orbit coordination, presenting a summary that can serve as basis for the development of a Best Practice on In-Orbit Phasing.

1.3 Reference Documents

[RD.1] CGMS-46-EUM-WP-15: Update of CGMS agency best practices in support to local and regional processing of LEO direct broadcast data.
[RD.2] CGMS-47-EUM-WP-09: Coordination of LEO orbits – An analysis

2 OUTCOME OF PRELIMINARY ANALYSIS ON LEO ORBIT COORDINATION

The analysis already performed for CGMS 47 [RD.2], highlighted that significant advantages would be attained through the alignment of repeat cycles (and therefore orbital altitude) of member agency missions on different orbital planes, leading to the reduction or elimination of ground station co-visibility scheduling conflicts. These advantages consist of:

- Increased efficiency in usage of shared ground stations, allowing more satellites to be supported or a reduction in required ground resources
- Maximising the amount of instrument observation collected (reducing need to prioritise between satellite mission acquisitions)
- Reducing of eliminating need to silence data collection or transmission due to radio frequency interference conflicts
- Better temporal separation between instrument observation
- Reduced risk of satellite proximity

The driving parameters to achieve a coordinated constellation of diverse LEO satellites were identified as illustrated in Figure 1:

- Orbital information of each satellite/constellation: altitude and orbital plane orientation, in terms of Mean Local Solar Time (MLST), along with in-orbit separations or actual positions (or relative positions). In addition, orbit maintenance strategy (that leads to oscillations in orbit around the actual reference in-orbit positions);
- Ground stations information: location, horizon masks, as well as turn-around time (between satellite passes in case same antenna to track both);

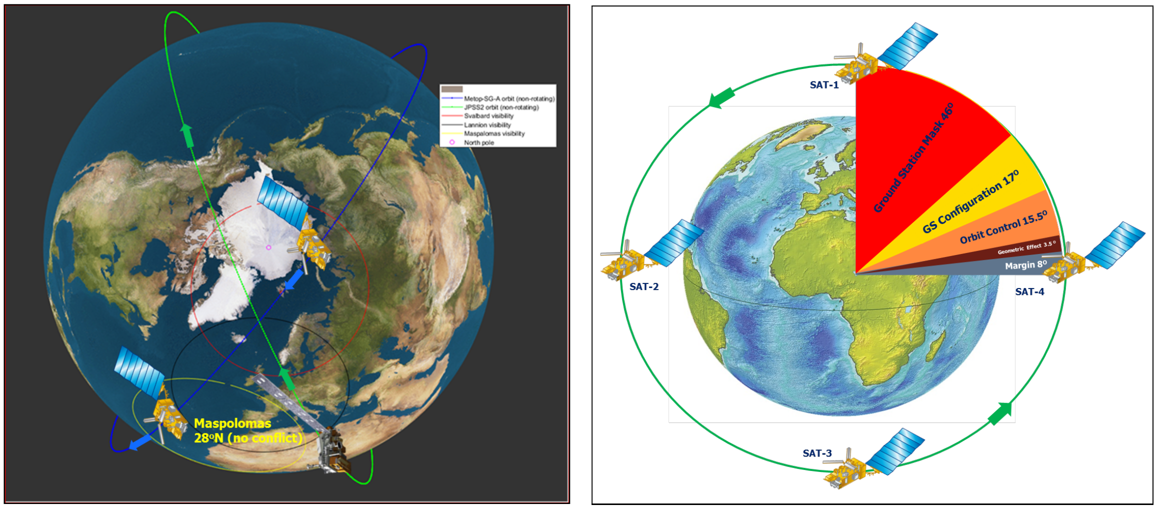


Figure 1: Consideration of Orbital Planes and inter-satellite constraints [RD.2]

Furthermore, with examples in both local mission direct broadcast and global mission polar dumps, other operational possibilities were highlighted to help optimise the synchronisation of the various satellite orbits, for example:

- Mission planned schemes for optimising local station acquisitions taking advantage of the predictable nature of any conflicts through the chosen repeat cycle.
- Limiting station acquisitions for global dumps to the time required, and eliminating potential conflicts though moving the scheduled dumps to different elevations according to a predefined, static schedule based on the repeat cycle orbit number.

Depending upon the separation of orbital planes and considered ground station locations, this approach would allow up to six satellites supported by a single ground station, without the need for any orbital manoeuvre coordination between agencies.

Adding another ground station antenna at the same site would therefore double this, taking into account the radio frequency interference constraints and therefore open up significant opportunities to the benefit of the CGMS members and their stakeholders.

3 OVERVIEW OF THE SIMULATION ALGORITHM

3.1 Algorithm Objectives and Structure

As proposed at CGMS-47, a prototype simulation tool has been developed at EUMETSAT to allow more detailed and specific analyses of LEO orbit coordination to be performed and provide outputs leading to the formulation of a Best Practice.

The simulation algorithm uses a two-step process as illustrated in **Error! Reference source not found.**. These steps split the algorithm into two parts as follows:

1. ***Two satellite problem algorithm***: The objective of this first algorithm is twofold:

   a. To determine the potential for in-orbit coordination by providing conflict statistics over any possible ground station location, between two satellites on the same or different orbit planes at any separation.
   b. To provide for specific use cases the driving separation constraints between two satellites flying at the same altitude on the same and different orbit planes. This output is then used in the second part of the algorithm to deduce the maximum number of satellites that can be placed in each plane for ensuring no conflicts (or maximization of on-ground data intake with minimum resources).

2. ***Constellation algorithm***: Based on the *two satellite problem* results, the objective is to determine the possible solutions for the maximum number of satellites in each orbital plane without conflict between them or those on the other orbital plane.

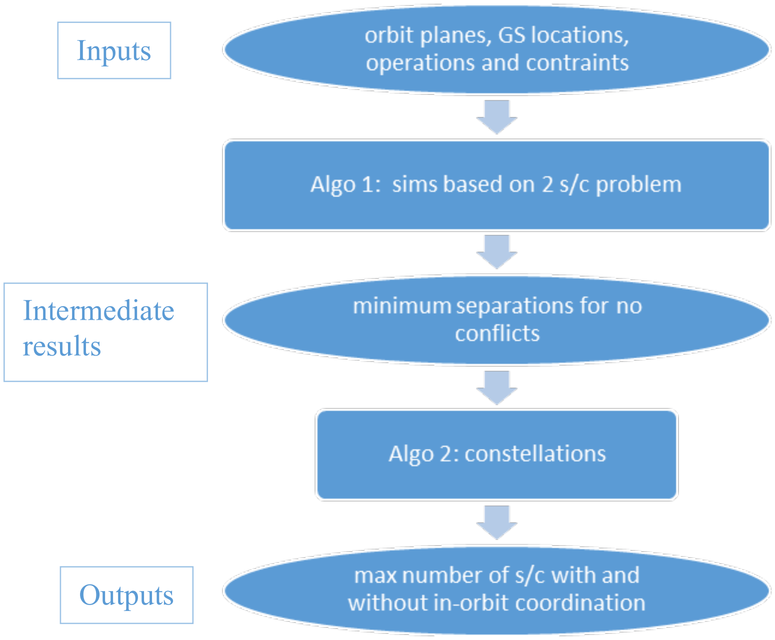


Figure 2: Simulation Algorithm Two-Step Process

3.2 Two Satellite Problem Algorithm

3.2.1 Input data

The following input data is required for each run of the simulation corresponding to a satellite pair for a specific satellite link type (global dump, direct broadcast, TT&C or RFI), on the same orbital plane or different orbital planes:

- Orbit altitude (repeat cycle and cycle length)[3]

---

[3] Altitude is never constant for a given orbit and highly depends on definition used. It is recommended to use repeat cycle and cycle length (examples: 4 days/57 orbits, 29 days/412 orbits) as this ratio defines altitude precisely and can be understood by everyone without ambiguities.

- MLST difference (delta-MLST) between orbital planes (or request to generate a range of output statistics at discrete delta-MLST values (e.g. 24 outputs for integer hour delta-MLST).
- Time margin between passes (to account for ground station turn-around and in-orbit control phasing worst case)
- Ground stations horizon masks (such as 0 degree, 5 degree, or given mask)
- Data acquisition strategy or options (flexibility), if available (such as not using all window available but placing data acquisition at start/mid/end of the available window)

3.2.2 Simulation Functional Overview

The simulation is executed for each satellite pair and link type, over the complete repeat cycle period (to ensure complete statistics). Theoretical ground stations are modelled in 2 degree steps around the orbit with interpolation between them, to ensure statistics at any latitude. The full range of possible satellite separations are simulated (from 0 to 360 degrees) with 2 degree step in-orbit separations. The algorithm can also be run at different delta-MLST steps.

3.2.3 Algorithm Design Notes

Given the large number of simulations required, as well as the relatively low fidelity necessary for this analysis, a simple analytical model is used. Circular constant orbital rate orbits are used, as this enables a very simple definition (purely geometric and based on constants that are obtained in advanced and directly from the provided inputs, i.e. orbit altitude and MLST: orbital plane inclination and orbital rate, initial longitude, earth rotation). Compared to higher fidelity orbits, these very simple orbits have maximum errors of about 40 km along-track (mainly due to the absence of eccentricity), that translates into an error of approximately 5 seconds when estimating visibility windows. With perigees typically around the North Pole, visibility windows are overestimated around the North Pole and underestimated around the South Pole).

Higher fidelity (eccentric orbits) could be obtained by adding Earth’s oblateness in the gravity field (J2) using semi-analytical theory, but this will significantly increase the computational time when long time spans and many orbit propagations are necessary.

3.2.4 Outputs

An output of conflict statistics is provided for any station location on Earth as well as for any satellite separation and these can be input into the *Constellation algorithm*.

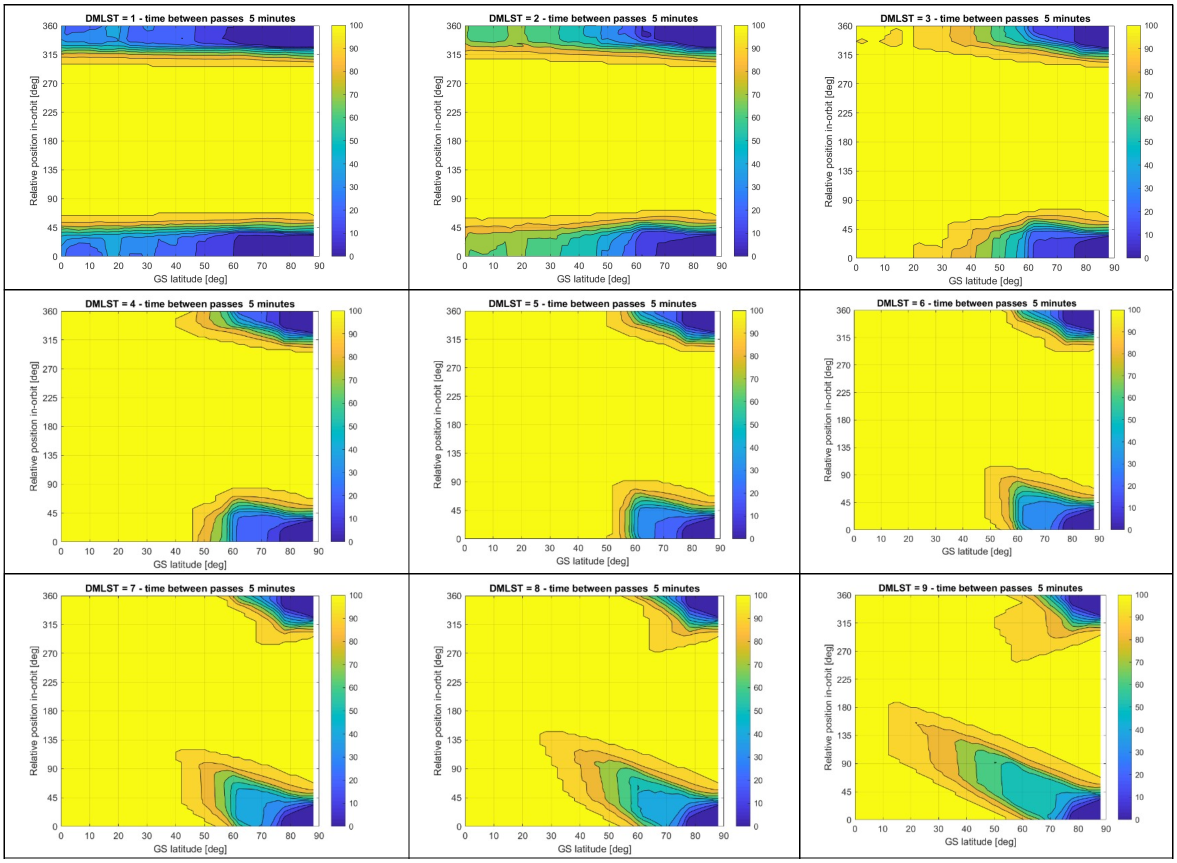
3.2.5 Example usage to assess potential for in-orbit coordination for any orbital plane configurations

If the user’s objective is to analyse conflict statistics to determine the potential benefits of in-orbit coordination on various satellite orbital plane configurations, the *two satellite problem* algorithm has to be executed multiple times in order to provide the desired level of statistical information.

The following input parameters were used:

- Satellites are on a 4 day/57 orbit (about 800 km altitude)
- 5 minute margin (station turn-around time plus station keeping margins)
- Full pass taken with AOS_5 to LOS_5

The simulation is performed over the 4 day repeat cycle.



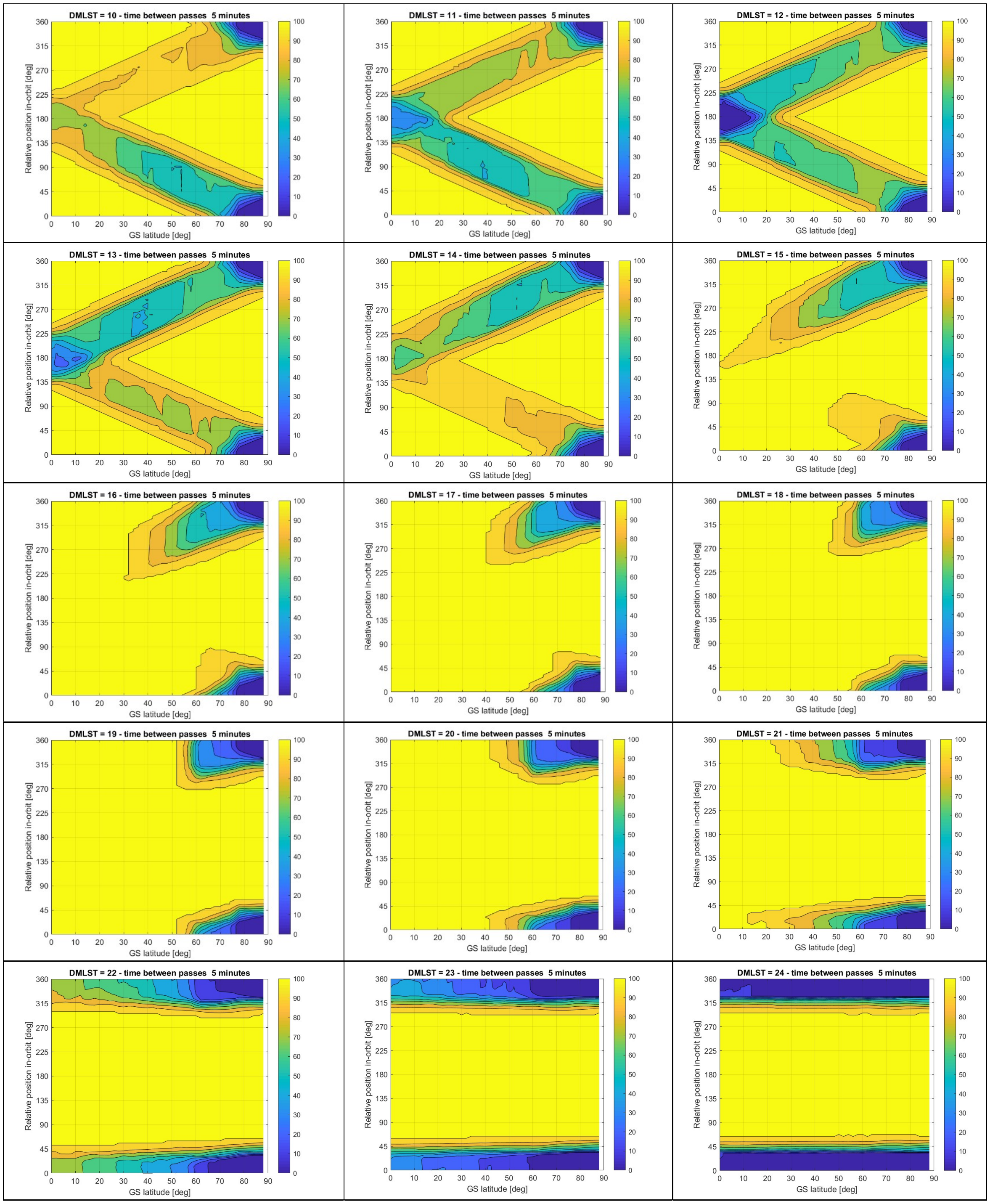


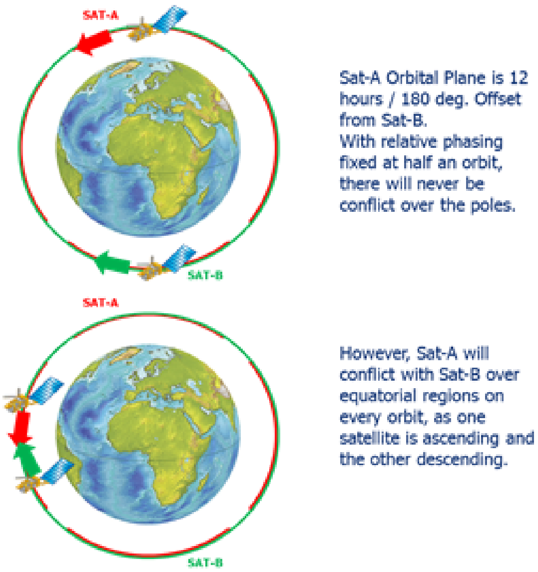
Figure 3: Two Satellite Problem output to analyse potential coordination benefits between various orbital planes.

With reference to Figure 3, each plot is made for a specific delta-MLST between the two planes (DMLST = 24 being the case of two satellites in the same orbital plane). It is assumed one satellite has priority and will always be supported by the available ground station pass. The colour scale indicates the percentage of passes that would be supported for the second, lower priority satellite from any station location and for any in-orbit separation between satellites. For a given ground station latitude, the possible range of phasing separation between the satellites where both satellites can be supported without conflict is indicated in yellow. The deep blue colour, on the other hand, indicates that for that latitude of ground station, the second satellite will always be in conflict with the primary satellite (and therefore would require a second ground station to have the potential to be supported from that location[4]).

Note: the results shown for MLST separations 1 to 12 hour should be the same as for the MLST separation 23 to 12, only that with inverted relative PSO values. The observed (insignificant) differences are only due to simulation artefacts).

If in-orbit positions are coordinated, i.e. satellites fly at same altitude and phasing controlled in-orbit (with margins), then this (constant) separation can be selected in order to minimize, or fully avoid, station conflicts (such as from end-users acquiring data broadcasted from the two satellites from a single antenna equipment).

The plots indicate that at large DMLST values (10 to 14 hours), it would not be possible to choose a phasing separation which is conflict-free at all ground station latitudes (case of opposing orbits as was provided as an example in CGMS-DOC-47 (see below)



Sat-A Orbital Plane is 12 hours / 180 deg. Offset from Sat-B.
With relative phasing fixed at half an orbit, there will never be conflict over the poles.

However, Sat-A will conflict with Sat-B over equatorial regions on every orbit, as one satellite is ascending and the other descending.

Figure 4: Conflicts with DMLST=12 hours

On the other hand, orbital plane separations with DMLST values from 1 to 9 hours (and 15 to 24 hours) do provide phasing separation possibilities for coordination where there are no conflicts at any ground station latitude. This would apply to orbital planes currently in use such as 3.5 hour (Fengyun-3E versus Metop) or 4.5 hour (Fengyun-3E versus JPSS) or 8 hours (Metop vs JPSS)

---

[4] Note that in this case, the simulation would need to be run again with the relevant RFI constraints to assess the extent to which a second ground station would mitigate the conflict.

3.2.6 Usage to analyse in-orbit coordination constraints for a specific orbital plane configuration

If the user wants to analyse the orbital coordination potential between two defined satellite systems in specific orbital plane configurations (i.e., a specific DMLST value), then the *two satellite problem* algorithm has to be executed three times: simulating two satellites in the first plane, two satellites in the second plane, and two satellites, each in a different plane.

These three runs of the *Two-satellite problem algorithm* will yield 4 parameters (see Figure 5) to be input into the *Constellation Algorithm* as follows:

- ***min_sep_A***, defined as the minimum separation to be respected between satellites in the first orbital plane (A constellation)
- ***min_sep_B,*** defined as the minimum separation to be respected between satellites in the 2nd orbital plane (B constellation)
- ***min_lead_sep_BA,*** defined as the minimum leading distance to be respected for any satellite in the 2nd orbital plane with respect to any satellite in the 1st orbital plane
- ***min_trail_sep_BA***, defined as the minimum trailing distance to be respected for any satellite in the 2nd orbital plane with respect to any satellite in the 1st orbital plane

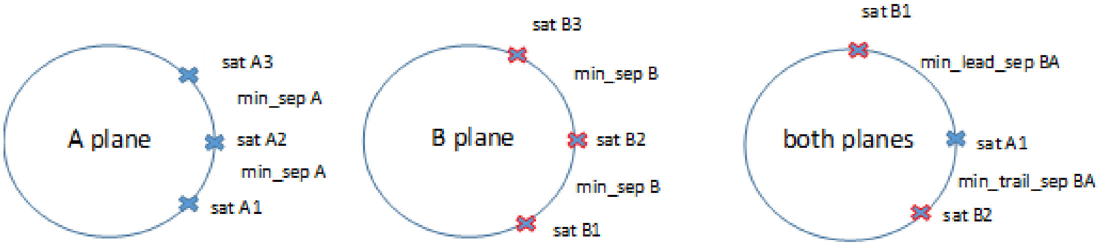


Figure 5: Output parameters from the Two-Satellite Problem Algorithm

Please refer to Section 4, which provides use case examples including the application of the follow-on Constellation algorithm as described in the next section.

3.3 Constellation Algorithm

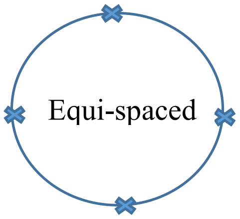
3.3.1 Input data

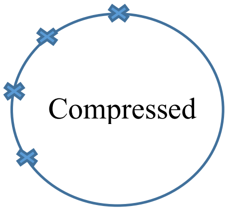
This second part of the simulation takes the results from two-satellite problem as input, along with the driving paramters (DMLST, ground station details etc.)

3.3.2 Simulation Functional Overview

The *Constellation Algorithm* assumes in-orbit phasing coordination between the two satellite orbital planes (satellites flying on the same repeat cycles at a defined DMLST). The second plane can accommodate satellites in-between the in-orbit position gaps left by the satellites in first orbital plane. The sequence and duration of gaps is dependent on how the satellites in the first plane are phased. The algorithm therefore considers the following two extreme cases:

- Satellites in first plane are equi-spaced in their orbit
- Satellites in first plane are compressed as much as possible





If satellites in the first plane are equi-spaced, then the actual separations between these satellites would be:

$$sep = 360 / i \qquad [deg]$$

With '*i*' being the number of satellites in plane 1 (< *Nmax_A)* and *'sep'* the actual separation.

If however satellites in first plane are compressed, then *i-1* satellites will be separated by *min_sep_A* separation while the other two will be left with a larger separation, which can be used as a gap for the other orbital plane:

$$i\text{-}1 \text{ with separation } sep1 = min\_sep\_A$$
$$1 \text{ with separation } sep2 = 360 - (i-1)*min\_sep\_A$$

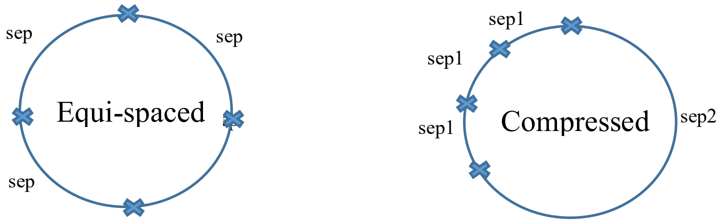


Figure 6: Equi-spaced and compressed orbital plane constellations

For each gap being left in-orbit by satellites in first constellation, the number of satellites of second constellation that can be inserted in it is given by the following formula:

if separation > min_lead_sep_BA + min_trail_sep_BA

```
        N_B_inBetween = ceil( (separation – min_lead_sep_BA – min_trail_sep_BA) / min_sep_B )
    else
        N_B_inBetween = 0
    end
```

Where *ceil* is the function returning the nearest integer towards larger numbers.

3.3.3 Example Output

Let us assume the following minimum in-orbit separations have been found to be necessary from the *two-satellite problem algorithm* (for conflict-free single antenna passes over a given ground station site or selection of sites):

- 66 degrees within the first plane (i.e. 5 s/c maximum in first plane)
- 50 degrees within the second plane (7 s/c maximum in second plane)
- Any satellite in the second plane at least 64 degrees leading or 88 degrees trailing from any spacecraft in first plane (to ensure no conflict).

The output of the *Constellation Algorithm* indicates the maximum number of satellites in the second orbital plane for any possible number of satellites (1 to 5) in the first plane as follows:

Nbr	A compressed		A equi-spaced	
A	B	A+B	B	A+B
5	0	5	0	5
4	1	5	0	4
3	2	5	0	3
2	3	5	2	4
1	5	6	5	6
0	7	7	7	7

Table 1: Constellation Algorithm output, Plane $A_{[0\ to\ max]}$

The table can also be constructed starting from plane B satellite numbers. The equivalent table would be as follows.

Nbr	B compressed		B equi-spaced	
B	A	A+B	A	A+B
7	0	7	0	7
6	0	6	0	6
5	1	6	0	5
4	1	5	0	4
3	2	5	0	3
2	3	5	2	4
1	4	5	4	5
0	5	5	5	5

Table 2: Constellation Algorithm output, Plane $B_{[0\ to\ max]}$

3.3.4 Interpretation of results

In this specific example, in-orbit coordination would allow to fly between 5 and 7 satellites in total, split in the two separate orbital planes, with no conflicts on shared, single antenna ground stations.

Note that with no in-orbit phasing coordination, a single satellite in one plane would conflict regularly with any satellite in the second orbital plane, making the total number of conflict-free satellites reduced to just 1 (meaning only the highest priority satellite can be acquired on those occasions.

Another lesson learnt that can be extracted from these results is the fact that compressed constellations allow for larger growth capacity than equi-spaced ones, but are most likely not optimal for user needs.

Note that the algorithm can be extended for any other intermediate or “mixed” cases between the two extremes of maximum compression and equidistant spacing.

4 USE CASES

In this section, more specific use cases, of relevant interest, are presented.

4.1 Uncoordinated Orbit Conflict Analysis

As discussed in [RD.2], CGMS Members typically operate their satellite missions on different orbital planes and with different repeat cycles with respect to other Member’s missions. For example, the sun-synchronous NOAA satellites (S-NPP, JPSS satellites) and EUMETSAT Metop satellites (also planned for Metop-SG satellites) orbital characteristics are indicated in Table 3.

	Metop	JPSS
MLST	21:30 ascending	13:30 ascending
Repeat cycle	29 days	16 days
Cycle length	412 orbits	227 orbits
Mean altitude wrt WGS84 equator	817 km	824 km

Table 3: Comparison of JPSS and Metop orbits

It can be observed that the choice of different repeat cycles is coupled with a small but crucial difference of altitude (7km), meaning that there is no relative phasing control between the NOAA and EUMETSAT satellites.

Dependent upon the orbital plane separation and the latitude of common ground stations, this relative phase rate may lead to occasional periods of close proximity where acquisition of data from both satellites is not possible. The periodicity of the return of the constellations to the same relative phase is known as the synodic period. For Metop/NOAA satellites it is calculated as follows:

- Metop/NOAA relative phase rate: is (412/29-227/16)*360 = 6.98 ° /day
  => synodic period 51.56 days (360/6.98)

This leads to a substantial period of time within this period where conflicts will arise over polar ground stations.

Figure 7 illustrates this effect on the NOAA/EUMETSAT Joint Polar System based on dump possibilities over the Svalbard Ground Station at 78.1 ° N. 2 Metop-SG satellites are phased half an orbit apart on one orbital plane and a single NOAA JPSS satellite (with lower dump priority than the Metop-SG satellites) on its own orbital plane. As can be seen, due to the relative phase rate, there is a beating effect where the satellite systems conflict on almost every orbit for over a week and then have a period of conflict free operations.[5]

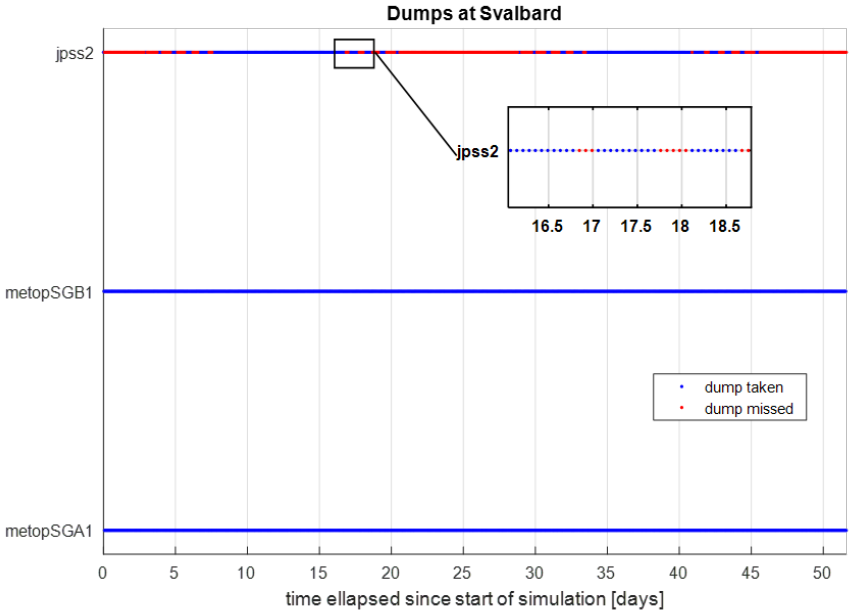


Figure 7: Conflicts over Svalbard due to Relative Phase Drift.

To illustrate this case further, the *two-satellite problem* algorithm is run with the following (assumed) input values:

- Mission A (Metop) needs 6 minutes of dump time, with margins, every orbit. Dumps are centred in the AOS/LOS window
- Mission A needs +/-2.5 minute in-orbit phase control window (derived from +/-2 minute orbit control in MLST and +/-10 km ground track control)

---

[5] Note that if the two MetopSG were phased more closely (~90°) the period during which one of the two interferes with JPSS become shorter because the two interference windows with the Metop-SG satellites overlap.

- Mission B (JPSS) needs 5 minutes of dump time, with margins, and are performed as soon as possible after AOS
- Mission B needs +/-1.5 minute in-orbit phase control
- Mission B flies at an MLST which is -8 (or +16) hour from mission A
- GS are located at latitudes about 78. ° N (equivalent to Svalbard) and 78. ° S (equivalent to McMurdo)
- 5 minute GS turn-around times are assumed.

Three runs of the algorithm are executed. Figure 8 shows the output of the simulation for the two satellites in the different planes. The following points can be deduced from this plot, assuming Mission A has priority for a given ground station resource:

- in order to secure a conflict-free acquisition of the satellite B in the same orbital timeframe, it cannot be within a separation range of [-160 °, +92 °] with respect to satellite A (i.e. satellite B leading by at least 92 ° or trailing by at least 160 °).
- for the specific case of acquiring the global dumps at the polar ground stations from the two satellites, the required separation of satellite B cannot be within the range [-88 °, +68 °] with respect to satellite A.

The Figure 8 also illustrates the reason for the beating effect seen in Figure 7. In this case of uncoordinated orbits, the relative phasing shown on the y-axis of Figure 8 is constantly changing, so it can be seen that at the Svalbard latitude, it is only when the relative phasing between a single Metop-SG and a single JPSS satellite is outside of the above mentioned separation range that no conflicts are guaranteed. This is clearly not the case for all orbits. Adding the second Metop-SG satellite, as is the case in Figure 7, reduces the conflict-free opportunities significantly.

Nevertheless, it is also apparent from Figure 8 that ground stations at lower latitudes (< 30 degrees) have the capability to acquire all satellites without conflict, despite the lack of phase control between satellites on the different orbital planes.

The other two runs of the *two-satellite problem algorithm,* (omitted here) provide 60 degree and 48 degree minimum separations for respectively satellites in same plane A or B and provided these are respected a single antenna at ground station site such as Maspalomas at 28 ° N would have conflict-free visibility to be able to acquire up to 6 Mission A satellites <u>and</u> 7 Mission B satellites[6]. With reference to Figure 1, this is explained by the geometry of the orbits (where the DMLST is high enough).

---

[6] The maximum number of satellites that could be co-located within each orbital plane, no account been given to the other orbital plane, would be:

$N_{max}\_A = floor(360/min\_sep\_A)$

$N_{max}\_B = floor(360/min\_sep\_B)$

With,

- '*floor*' being the function returning the nearest integer towards lower values
- '*min_sep_A*' and '*min_sep_B*' being the minimum satellite separations required between respectively satellites A only and satellite B only.
- 'N_{max}_A' and 'N_{max}_B' being the maximum number of satellites that can be put in each orbital plane

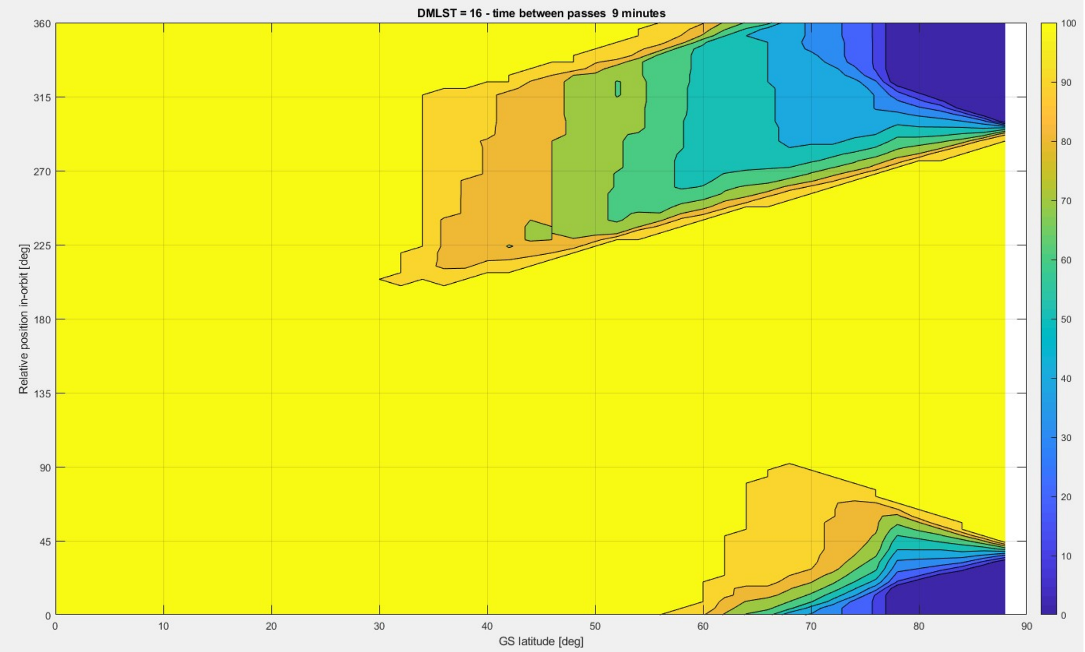


Figure 8: JPSS-Metop Station conflicts at higher latitudes.

In the event of fully independent on-ground resources, or for ground stations at sufficiently lower latitudes, no further coordination would be needed. If however, as is the case, some shared on-ground resources are required at higher latitudes, such as the McMurdo global dump station or Direct Broadcast stations covering the Northern Atlantic region for example, then there will be conflicts to be managed through prioritisation schemes. Some mitigation through scheduling flexibility measures could be considered in addition (e.g. coordinated scheduling of dump times within a ground station visibility window). This may add significant complexity to operations ground system functionality and interactions however.

4.2 Coordinated Orbits to Optimise Global Data Dumps at Polar Stations

In this section, we continue with the example of Metop and JPSS and look at the impact of coordinating their repeat cycles at their assigned MLST orbital planes in order to improve usage of shared polar station resources for global mission data dumps, maximising overall efficiency.

For the purpose of the simulation, it is assumed that orbits are coordinated according to the current JPSS repeat cycle, implying a change of 7 km altitude with respect to the current Metop orbit (refer to Table 3). Apart from this slight change in orbit, the *two-satellite problem* algorithm is run with exactly the same input parameters as described in the previous Section. The effect of the 7 km difference in orbital altitude and associated repeat cycle is so small that it is not visible in the output plot (refer to Figure 8).

Applying now the *Constellation Algorithm,* the following possibilities and maximum number of satellites could fly concurrently in conflict free configurations using a single ground antenna resource at the polar stations.

Nbr	A compressed		A equi-spaced	
A	B	A+B	B	A+B
6	0	6	0	6
5	0	5	0	5
4	1	5	0	4
3	2	5	0	3
2	3	5	2	4
1	5	6	5	6
0	7	7	7	7

Table 4: Potential for LEO Orbit Coordination using a Metop/JPSS Example

In this particular example, each constellation may operate up to 6 satellites (for constellation 1) or 7 satellites (for constellation 2) in their plane without sharing any ground station resource for global dumps (case discussed in the previous, uncoordinated orbit section). However, if ground station antennas are however to be shared without the need for any dynamic scheduling interactions between the two missions, LEO orbit coordination is required (same altitude) and the following example possibilities exist:

- a total of 5 satellites in-orbit, 3 of one constellation, 2 of the other constellation, sharing resources (a single antenna for global dumps) conflict-free
- constellation 1 could operate up to 4 satellites in its orbit and still provide support with single antenna and conflict free to one satellite (appropriately phased) on the second constellation
- constellation 2 could operate up to 5 satellites in its orbit and still provide support with single antenna and conflict free to one satellite (appropriately phased) on the first constellation

Additional measures which could lead to the ability to support an increased number of satellites were described in [RD.2], such as:

- predefining along the repeat cycle optimised dump schedules starting at different points in a pass visibility according to the expected co-visibility with the second mission's satellite. Provided each operator adheres to their manoeuvre window margins, no dynamic scheduling interaction would be required.
- reducing the MLST control window which would provide additional margin, but at the cost of more frequent manoeuvres. This trade-off could be beneficial if fuel lifetime is not a significant driver for the mission.
- The phasing of a larger number of satellites / orbital planes could also be optimised to ensure the coordination of those satellites performing primary operational services, with lower priority satellites accepting some occasional conflicts.
- More complex operational interactions involving the synchronisation of manoeuvres between satellite mission operators could bring maximum benefit in terms of data acquisition over common ground facilities, but benefits are likely to be marginal for the effort required, compared to that achievable from the other, predefined, static measures.

4.3 Direct broadcast mission data acquisition from single antenna user

This example shows the case of “local” users acquiring data with a single antenna from two separate satellite constellations. A -3.5 hour MLST separation is selected (reflecting the case of Metop versus Fengyun 3E). This case is also largely representative of the case SNPP/JPSS versus Fengyun 3E (4.5 hour orbital plane separation).

In this case, we assume that data is acquired over the entire passes and at elevations as low as 0 degree. This can also happen everywhere on Earth (station locations everywhere). Antenna turn-around times are shorter: 2 minutes. Station keeping margins are kept similar as in previous case (2.5 and 1.5 minutes for respectively satellite missions A or B).

The minimum separation of any satellite in the second plane with respect to any satellite in first plane is [-96 °, +76 °] as shown in Figure 9.

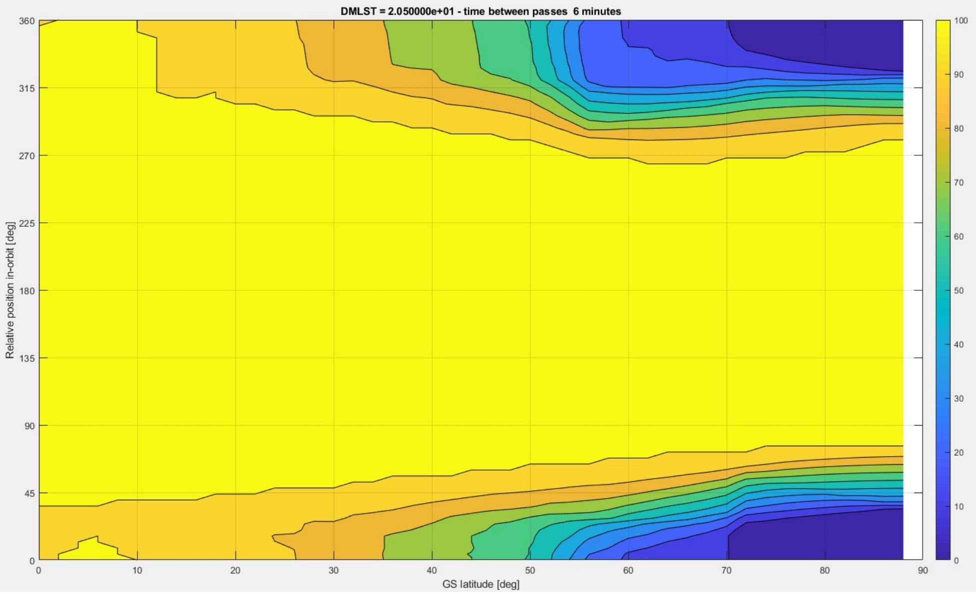


Figure 9: Metop separation constraints with Fengyun 3E for Direct Broadcast Users

Additional runs of the *two-satellite problem algorithm* show that 84 ° and 76 ° minimum separations would be necessary for conflict-free configurations within planes A and B respectively. This would allow the deployment of four satellites in each plane without conflict between those satellites.

However, with no orbit coordination as is currently the case, there will be regular conflicts between the satellites in the two planes, increasing depending upon how many satellites are operated. This is analogous to the case of polar station conflicts illustrated in Figure 7.

If in-orbit phasing coordination were to be used (see Table 1), up to 3 satellites could be operated and remain conflict free (all data acquired for all 3 satellites from any single user station located anywhere in the globe). 4 satellites (2 in each plane) would be possible from most station locations (but not all), or with reduced margins or using higher horizon masks.

Nbr	A compressed		A equi-spaced	
A	B	A+B	B	A+B
4	0	4	0	4
3	0	3	0	3
2	1	3	0	2
1	2	3	2	3
0	4	4	4	4

Table 5: Potential for LEO Orbit Coordination using a Metop/FY3E Example

4.4 Radio Frequency Interferences

Radio frequency interferences have not yet been addressed in the prototype simulation algorithms. It is clear that if satellites are in no conflict from a single antenna usage on-ground stand-point, then they will also be RFI free. However, smaller separations in-orbit, while not sufficient for on-ground optimization of resources (conflict-free configurations as identified earlier), may still be sufficient for avoiding RFIs only (i.e. conflict free from the RFI standpoint).

It is important to note that while the impact of uncoordinated orbits on ground antenna visibilities can be mitigated through installation of additional ground antennas, this will not solve the RFI conflicts for antennas located in the same geographical vicinity.

For the case of JPSS versus Metop (second generation) operating with their independent repeat cycles, both satellites will be transmitting in the same Ka-Band with an associated high potential for RFI events over the Svalbard or McMurdo polar sites, due to the frequent conflicting passes over these sites as already explained in Section 4.1.

Simple geometry shows that any two orbital planes cross by definition at two points (even if at different altitudes, but with altitude difference negligible compared with actual orbit altitudes or range distances). In the case of 98.6 ° to 98.7 ° inclined planes, one at 13:30 ascending (for any SNPP/JPSS satellite), the other at 9:30 descending (for any Metop satellite), it can be demonstrated, and fully supported by simulations, that all RFIs occur when the two satellites are around the following two positions in-orbit:

- Over northern hemisphere: 104.7 ° for Metop-SG and 75.3 ° for JPSS
- Over southern hemisphere: 284.7 ° for Metop-SG and 255.3 ° for JPSS

In both cases, relative in-orbit separations around 29.4 °, +/- 2 ° (Metop ahead of JPSS) would need to be avoided. This can only be achieved through in-orbit coordination (implying both satellite fleets flying at same altitudes). Otherwise it will not be possible to prevent RFIs to occur on an occasional basis (in the case of Metop and JPSS, with a potential synodic period of about 51.6 days between any satellite pair). With several of these satellites in the same orbital plane, the RFI occurrences increase linearly with the number of satellites.

Simulations show that these RFI events are only as long as one minute. However, in-orbit manoeuvre margins need to be added, incrementing the 1 minute window to around 5 minutes for the Metop-SG/JPSS case.

With such a small relative separation window to be avoided, the advantage of in-orbit coordination is significant, since it allows full capacity to be deployed on the different orbital planes (such as 4 or more satellites per plane) while phasing them appropriately to further eliminate, fully, any risk of RFI events among any satellite pair. Moreover, a third constellation plane could be added into the picture (Figure 10), crossing the previous ones at different relative positions, with specific in-orbit relative positions to be avoided for preventing RFIs with the others. In orbit phase coordination between all three orbital planes (all flying at same altitudes) would allow selecting a relative phasing between all the different satellites in the three planes to avoid RFIs between all of them.

Therefore, where multiple antennas on the same site are required to serve the different missions, these could be scheduled, without risk of RFI, to allow a minimal spacing between satellites, increasing the overall capacity of the coordinated satellite missions.

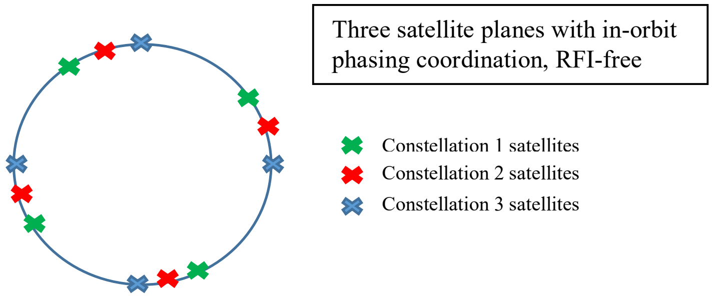


Figure 10: Possible three mission constellation avoiding RFI

5 SUMMARY OF BENEFITS

In summary, there are clear benefits for CGMS members and their user communities in coordinating the LEO orbits to align the repeat cycles (altitude), irrespective of which orbital plane Mean Local Solar Time is preferred. These benefits can be further enhanced through coordinating the respective missions' MLST values, both from the perspective of further optimising the satellite capacity of each orbital plane and from the user data perspective.

The benefits are summarised as follows:

- Reduction of ground station resources required and therefore long-term operational costs, by preventing conflicting passes. This especially applies to polar station sites used for global mission dumps.
- Maximising the amount of data collected, avoiding loss of “lower priority” data due to pass or RFI conflicts. Note that such data may well be classified as lower priority from the perspective of the ground station owner who naturally prefers to acquire their own satellites, rather than lose data in favour of another operator’s satellite, whereas its acquisition remains valuable to the user community.
- The fixed conflict pattern over local stations across the globe allows optimisation of data collection from all supported satellites on coordinated orbits, since over the repeat cycle, any conflict events are repeated.
- Elimination of RFI events from concurrent passes using separate antenna. Where maximum utilisation of coordinated orbital planes is required (especially relevant where three or more orbital planes are coordinated), then multiple ground station antenna on a given site can be used to resolve pass visibility conflicts, but the fixed separation of passes can be designed to ensure these will never suffer radio frequency interference. This will again maximise user data.
- Avoiding need to remove older generation satellites from an orbital plane. Typically satellite operational lifetimes are substantially longer than their required, design lifetime, leading to overlaps of new satellite programmes with the previous generation. Through coordination of orbital planes, the operational cost of these satellites can be reduced since they may continue to share ground resources, thereby potentially allowing lifetime extensions to become more affordable.
- Fixed temporal separation of mission data acquisition can help reduce communications costs, as it averages out the data collection profile over time, avoiding driving requirements from peak worst cases.
- This temporal separation is also likely to be more efficient and effective for end-users’ assimilation processes.

Note that with respect to satellite proximity, the coordinated orbits will ensure that each mission’s satellites are well separated and pose no conjunction threat to other coordinated orbits. However, satellites operating at different altitudes will also generally pose no threat to each other, so satellite proximity should not be considered as a specific driver for the assessment.

Clearly, effort would be required to analyse the coordination possibilities and agreements on shared ground facilities development and maintenance will be more complex from a programme development management perspective than simply procuring dedicated, independent resources for each programme. Given the foreseen duration of supported missions and the expected lifetime of ground facilities (which may span more than one mission), it would be expected that this effort could provide significant programme cost savings over the operational lifetimes of the mission, along with the above mentioned user benefits in terms of increased data return.

The above benefits and definition of associated coordination tasks to achieve these results can form the basis of the Best Practice foreseen by Action A47.11.

Note this Best Practice shall consider lead times in programme planning in order to reach the agreements, noting that foreseen missions from various CGMS members may not be aligned in terms of deployment dates.

It should also consider the potential to align existing in-orbit or future missions which have already been defined with independent, non-coordinated orbits. Criteria for trade-offs in pursuing such a path should be established.

Further work should also be performed on this prototype algorithm to provide analysis results for optimising orbital configurations to avoid radio frequency interferences between satellite system operating on multiple orbital planes, where more than one antenna is available at a specific ground station site.

6 ACTIONS AND/OR RECOMMENDATIONS FOR CONSIDERATION BY CGMS WORKING GROUP I

Concerning the existing open action:

Action A47.10 *to perform a more detailed analysis consisting of:*
- *developing a simulation algorithm considering all identified variables impacting the LEO orbit coordination*
- *developing plots and other simulation outputs as tools for illustrating the potential coordination possibilities and improvements in both global and direct broadcast mission return.*

This Paper has provided a prototype simulation algorithm covering all the identified variables impacting LEO orbit coordination, and some example plots and outputs.

Recommendation on A47.10: It is recommended that the simulation algorithm and outputs presented in this Paper are reviewed by CGMS Member experts in mission analysis to:
- ascertain the applicability to operational and planned missions
- determine further work required on the prototype simulation tool.
- assess its role in the formulation of a Best Practice on coordination of LEO orbits (Action A47.11).

7 CONCLUSIONS

CGMS Working Group I Members are invited to take note of this Paper and the associated Recommendation.