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Assessment of Mission Scenarios and Definition of OSSE Study Test Missions

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Contents

1 Introduction

This assessment and definition study builts directly on the mission scenario study reported in [MISSTUD99]. In that study we analyzed 39 satellite constellation scenarios, called "realistic scenarios", which were representing 21 different satellite constellation cases. The number of scenarios under study exceeded the number of actual constellations since for cases involving more than one orbit plane inclination we always investigated two complementary orbit node situations, maximal node alignment and maximal node dispersion, respectively.

The aim of this study was to downselect, by means of a quantitative assessment based on objective performance descriptors, from the 21 candidate constellations of [MISSTUD99] to a small "best" sample of constellations, which can subsequently be used as representative test missions for Observation System Simulation Experiments (OSSE) carried out in order to investigate the impact of GNSS occultation data on numerical weather prediction (NWP) systems. (See the proposal document [APNWP98] for details on the full OSSE study plan.)

Having the very significant resource demands required for a realistic OSSE study in mind, the OSSE study team decided to have a maximum of four OSSE test missions finally defined. These four test missions should include in any case a single sun-synchronuous satellite mission, as a fixed basic "zero-level" reference case. This reference case is to mimic the situation of having just a single GNSS receiver for atmospheric sounding (GRAS) available in orbit, e.g., the METOP/GRAS instrument scheduled for launch in 2003 with the METOP-1 satellite of the European Polar System (EPS).
Given these generic constraints, we will destill a set of three constellation cases in this report (more precisely speaking, two alternative sets of three constellation cases), which we recommend as test missions for the OSSE study.

Section 2 summarizes the [MISSTUD99] input and the general constraints imposed on the definition. Section 3 introduces the objective performance descriptors – we employed a penalty function approach – on which we based the quantitative assessment of the 21 candidate constellations. The results of the assessment are worked out and discussed in section 4 and in section 5 we finally perform our actual definition of "best" constellations and formulate our recommendations for OSSE study test missions.

2 Mission Scenario Study Input and Definition Constraints

The input from the [MISSTUD99] study and the general constraints can be summarized as follows.

Input: The results computed for the 39 "realistic mission scenarios" of [MISSTUD99].
These 39 scenarios included 13 6-satellite, 13 12-satellite, and 13 24-satellite ("3 x 13") scenarios, respectively, which correspond in terms of actual constellations to 7 6-satellite, 7 12-satellite, and 7 24-satellite ("3 x 7") constellations, respectively.
The results comprised, for each of the 39 scenarios, five statistical measures of performance (see Section 3.3 of [MISSTUD99] for details): (i) Total number of occultation events per unit area, N, (ii) mean horizontal sampling distance between

neighbor occultation events, $\bar{d}$, (iii) sampling distance dispersion, σ_d, (iv) mean time separation between neighbor occultation events, $\bar{t}$, and (v) time separation dispersion, σ_t, respectively. Each of these measures was computed globally but also for geographical subregions of the globe, with cells of size 15° lat. × 60° lon. as smallest partitions.

General Constraints: A set of maximally four OSSE test missions was agreed on by the study team. This shall include a single sun-synchronuous satellite case as "zero-level" baseline, leaving three actual constellations to be defined. We impose the further constraint, that at least one 6-satellite, one 12-satellite, and one 24-satellite constellation shall belong to the OSSE test mission sample. Thus we will destill a set of three constellations, or alternative sets of three constellations offered for final decision to the team, comprising one 6-sat, one 12-sat, and one 24-sat constellation ("3 x 1" choice).

The assessment and definition work to be performed is thus the following: Using the statistical performance measures of the 39 ("3 x 13") scenarios from [MISSTUD99] as input, quantitatively assess them by computing objective performance descriptors – including a single total figure-of-merit – for each of the 21 ("3 x 7") candidate constellations. Then rate the "3 x 7" constellations based on their descriptors and destill 3 final cases ("3 x 1", i.e., one 6-sat, one 12-sat, one 24-sat), or alternative sets of 3 final cases, to be recommended as OSSE test missions.

3 Performance Descriptors for the Assessment

3.1 The Penalty Function Concept

We employed a penalty function concept for defining sensible integral performance descriptors for the candidate constellations, based on the information we have in form of the statistical performance measures from [MISSTUD99].
This is an attractive concept since it allows, for each of the 39 input scenarios, to sensibly and very effectively collapse the information contained in the extremely high-dimensional parameter space of the statistical performance measures into a low-dimensional penalty function space, i.e., a small number of scalar figures-of-merit, finally even a single figure-of-merit in form of a total penalty value for each given constellation.
Such a dimension-reduction mapping is intrinsically highly ambiguous, however, and there exists basically an infinite number of possibilities to define penalty functions as functions of all the statistical measures information we have available from [MISSTUD99].
It is thus important to note that our choice below is what we found a sensible penalty definition given our experience in the field. In other words, though the subsequent assessment (section 4) is indeed performed objectively based on the defined performance descriptors, the setup of the objective framework itself (here our penalty function definitions) is always based on (subjective) experience. This should (always) be kept in mind when judging (the) objective assessment results.

3.2 Definition of Penalty Functions

We defined the following seven penalty functions as our basic objective performance descriptors:

- (1) Sampling Requirements Penalty J_d
- (2) Mission Cost Penalty J_c
- (3) Event Number Penalty J_N
- (4) Unequal Coverage Penalty J_{σ_N}
- (5) Geographic Irregularity Penalty J_{σ_d}
- (6) Time Separation Penalty J_t
- (7) Time Irregularity Penalty J_{σ_t}

Furthermore, we defined a "Total Penalty", J_{tot}, which shall be a (user-)weighted and normalized sum of the 7 specific penalties (1) – (7).

The names of the penalties were chosen to be suggestive of what aspect of constellation performance they "penalize", i.e., a penalty value for a given aspect will be the lower the better this aspect is fulfilled by a constellation scenario. To give one or two examples: An "Event Number Penalty" will certainly be higher for a 6-sat constellation than for a 24-sat constellation, since the latter, favorably, furnishes much more events per unit area and unit time. For a sensible "Mission Cost Penalty" it is clearly the other way round.

The quantitative formulation of the penalty functions for the alltogether eight penalties listed above, was chosen as follows:

- (1) Sampling Requirements Penalty J_d:

$$J_d = f_d F_d; \quad F_d = \frac{\overline{d}^{gl}}{(\overline{d}_{ref})}; \quad (\overline{d}_{ref}) = 300 \text{ [km/6hrs]}; \quad f_d = 1 \text{ (baseline)}$$

  The input statistical measure to J_d is $\bar{d}^{gl}$, the global average mean distance between neighbor occultation events per unit time. The factor f_d allows to weigh J_d relative to the other six specific penalties.

- (2) Mission Cost Penalty J_c:

$$J_c = f_c F_c; \quad F_c = g_{sat}(1 - g_{sunsync}\frac{n_{sunsyncsat}}{n_{sat}})\frac{n_{sat}}{(n_{ref})} + g_{orb}\frac{n_{orbplanes}}{(n_{orbref})};$$

$$g_{sat} = 1/4; \quad g_{sunsync} = 1/4; \quad g_{orb} = 1/2;$$

$$(n_{ref}) = 6 \text{ [sats]}; \quad (n_{orbref}) = 2 \text{ [planes]}; \quad f_c = 1 \text{ (baseline)}$$

  The input measures to J_c are the number of sats in the constellation, n_{sat}, the number of sun-synchronuous sats in the constellation, $n_{sunsyncsat}$, and the number of orbital planes involved, $n_{orbplanes}$. The factor f_c allows to weigh J_c relative to the other six specific penalties.

- (3) Event Number Penalty J_N:

$$J_N = f_N F_N; \quad F_N = \frac{(N_{ref})}{N^{gl}}; \quad (N_{ref}) = 5\ [/(1000\text{km}^2)/6\text{hrs}]; \quad f_N = 1 \ \ \text{(baseline)}$$

The input statistical measure to J_N is N^{gl}, the global average number of occultation events per unit area and time. The factor f_N allows to weigh J_N relative to the other six specific penalties.

- (4) Unequal Coverage Penalty J_{σ_N}:

$$J_{\sigma_N} = f_{\sigma_N} F_{\sigma_N}; \quad F_{\sigma_N} = \frac{\tilde{\sigma}_N^{gl}}{(\tilde{\sigma}_{N,ref})}; \quad (\tilde{\sigma}_{N,ref}) = 33\ [\%]; \quad f_{\sigma_N} = 1 \ \ \text{(baseline)}$$

The input statistical measure to J_{σ_N} is $\tilde{\sigma}_N^{gl}$, the (relative) global "coverage inhomogeneity index" (cf. [MISSTUD99], section 3.3.2). The factor f_{σ_N} allows to weigh J_{σ_N} relative to the other six specific penalties.

- (5) Geographic Irregularity Penalty J_{σ_d}:

$$J_{\sigma_d} = f_{\sigma_d} F_{\sigma_d}; \quad F_{\sigma_d} = g_{\tilde{\sigma}_d} \frac{\tilde{\sigma}_d^{gl}}{(\tilde{\sigma}_{d,ref})} + g_{\sigma_d^A} \frac{\sigma_d^{A,gl}}{(\sigma_{d,ref}^A)}; \quad g_{\tilde{\sigma}_d} = 1/2; \quad g_{\sigma_d^A} = 1/2;$$

$$\sigma_d^{A,gl} = \left[\frac{1}{N_A - 1} \sum_{i=1}^{N_A} \left(\sigma_{d,i}^A - \sigma_d^{gl} \right)^2 \right]^{\frac{1}{2}}; \quad (\tilde{\sigma}_{d,ref}) = 33\ [\%]; \quad (\sigma_{d,ref}^A) = 100\ [\text{km}];$$

$$f_{\sigma_d} = 1 \ \ \text{(baseline)}$$

The input statistical measures to J_{σ_d} are σ_d^{gl} and $\tilde{\sigma}_d^{gl}$, respectively, the (absolute and relative) global "geographic irregularity indices" (cf. [MISSTUD99], section 3.3.2), and the $\sigma_{d,i}^A$ values, the sampling distance dispersions for the 36 lat x lon cells of [MISSTUD99] ($i = 1, \ldots, N_A$, $N_A = 36$; cf. [MISSTUD99], setion 3.3.2). The factor f_{σ_d} allows to weigh J_{σ_d} relative to the other six specific penalties.

- (6) Time Separation Penalty J_t:

$$J_t = f_t F_t; \quad F_t = \frac{\bar{t}^{gl}}{(\bar{t}_{ref})}; \quad (\bar{t}_{ref}) = 60\ [\text{min}/6\text{hrs}]; \quad f_t = 1 \ \ \text{(baseline)}$$

The input statistical measure to J_t is $\bar{t}^{gl}$, the global average mean time separation between neighbor occultation events per unit time. The factor f_t allows to weigh J_t relative to the other six specific penalties.

- (7) Time Irregularity Penalty J_{σ_t}:

$$J_{\sigma_t} = f_{\sigma_t} F_{\sigma_t}; \quad F_{\sigma_t} = g_{\tilde{\sigma}_t} \frac{\tilde{\sigma}_t^{gl}}{(\tilde{\sigma}_{t,ref})} + g_{\sigma_t^A} \frac{\sigma_t^{A,gl}}{(\sigma_{t,ref}^A)}; \quad g_{\tilde{\sigma}_t} = 1/2; \quad g_{\sigma_t^A} = 1/2;$$

$$\sigma_t^{A,gl} = \left[\frac{1}{N_A - 1} \sum_{i=1}^{N_A} \left(\sigma_{t,i}^A - \sigma_t^{gl} \right)^2 \right]^{\frac{1}{2}}; \quad (\tilde{\sigma}_{t,ref}) = 33\ [\%]; \quad (\sigma_{t,ref}^A) = 20\ [\text{min}];$$

$$f_{\sigma_t} = 1 \quad \text{(baseline)}$$

The input statistical measures to J_{σ_t} are σ_t^{gl} and $\tilde{\sigma}_t^{gl}$, respectively, the (absolute and relative) global "time irregularity indices" (cf. [MISSTUD99], section 3.3.2), and the $\sigma_{t,i}^A$ values, the time separation dispersions for the 36 lat x lon cells of [MISSTUD99] ($i = 1, \ldots, N_A$, $N_A = 36$; cf. [MISSTUD99], setion 3.3.2). The factor f_{σ_t} allows to weigh J_{σ_t} relative to the other six specific penalties.

- Total Penalty J_{tot}:

$$J_{tot} = \frac{1}{7}\sum_{k=1}^{7} J_k = \frac{1}{7}\sum_{k=1}^{7} f_k F_k, \qquad k \in \{d, c, N, \sigma_N, \sigma_d, t, \sigma_t\}$$

or written more explicitely

$$\begin{aligned} J_{tot} &= J_d + J_c + J_N + J_{\sigma_N} + J_{\sigma_d} + J_t + J_{\sigma_t} \\ &= f_d F_d + f_c F_c + f_N F_N + f_{\sigma_N} F_{\sigma_N} + f_{\sigma_d} F_{\sigma_d} + f_t F_t + f_{\sigma_t} F_{\sigma_t} \end{aligned}$$

We have implemented this penalty function formulation in a computational routine (IDL program), with the weighting factors f_k being user-definable input parameters; the baseline setting is unity for all f_k's as indicated above. It is up to the assessment responsible to specify the weighting among the specific penalties; the relative weighting supplied is automatically normalized to unity by enforcing $\frac{1}{7}\sum_{k=1}^{7} f_k = 1$.

3.3 Computation of Performance Descriptors

We computed the eight performance descriptors (penalty values) for all 39 realistic scenarios of [MISSTUD99]. In practice, after the weighting factors f_k are defined by the user of the computational routine referred to above, the routine normalizes them and then automatically produces all values for each of the 39 scenarios.

For the assessment results reported below we set the f_k's such that we assigned equal weights of $f_k = 1.15$ to all penalties except the geographic irregularity and time irregularity penalties, J_{σ_d} and J_{σ_t}, respectively. To the latter we assigned roughly half the weight of the others ($f_{\sigma_d} = f_{\sigma_t} = 0.62$). This weighting reflects that we consider the two latter penalties more of "2^{nd} order" importance relative to the other five. This is well justified given that these are the two descriptors which are just dispersion measures of the "1^{st} order" descriptors J_d and J_t (note that J_{σ_N} is a dispersion measure for the "0^{th} order" descriptor J_N, however). We decided not to impose any further more subtle weighting due to lack of convincing rationale.

Using this weighting we computed the eight descriptors, the J_k's and J_{tot}, for the 39 scenarios. The needed input parameters, namely $\bar{d}^{gl}$, n_{sat}, $n_{sunsyncsat}$, $n_{orbplanes}$, N^{gl}, $\tilde{\sigma}_N^{gl}$, σ_d^{gl}, $\tilde{\sigma}_d^{gl}$, $\sigma_{d,i}^A$ ($i = 1, \ldots, N_A$; $N_A = 36$), $\bar{t}^{gl}$, σ_t^{gl}, $\tilde{\sigma}_t^{gl}$, and $\sigma_{t,i}^A$ ($i = 1, \ldots, N_A$; $N_A = 36$), were available from the [MISSTUD99] result files containing the statistical measures and were read in from there.

Based on the descriptors for the 39 ("3 x 13") scenarios, the descriptors for the 21 ("3 x 7") actual constellations had to be obtained. Recall from [MISSTUD99] that for all constellations, except the 3 ("3 x 1") pure sun-sync ones, we had different inclinations of orbital planes involved and we thus investigated both maximal node alignment ($\Delta\Omega_{min} =$

0 deg) and maximal node dispersion ($\Delta\Omega_{max} = 90\,\mathrm{or}\,45$ deg) scenarios, respectively, for these alltogether 18 ("3 x 6") constellations.
We computed the eight descriptors, generically denoted as J_l's, for the 18 constellations as

$$J_l = \frac{1}{2}(J_l^{\Delta\Omega_{max}} + J_l^{\Delta\Omega_{min}}); \quad l \,\epsilon\, \{d, c, N, \sigma_N, \sigma_d, t, \sigma_t, tot\},$$

i.e., we simply averaged the results of the two node separation scenarios of each mixed-inclination constellation. No such further treatment was of course needed for the descriptors of the three pure sun-sync constellations as these J_l's directly correspond to single scenario results.

Should the J_l's, most notably the total figure-of-merit J_{tot}, not lead to an unique conclusion on three final constellations, we have the option to proceed with invoking more sophisticated descriptors than the scalar J_l's. To next level in complexity these are "vector descriptors", i.e., distributions of statistical measures over some coordinate. We find it sensible, from an observational and user requirements point of view, to consider as "vector descriptor" of primary relevance the number of occultation events per unit area and unit time vs. geographic latitude, which we denote $N(\varphi)$.
As described in section 4 below, the J_l's indeed are not fully conclusive (section 4.2) and we thus have used $N(\varphi)$ histogram functions for an assessment refinement (section 4.3). The simulations and the visualization of the $N(\varphi)$ histograms have been performed with the "Mission Analysis/Planning" functionality of the End-to-end GNSS Occultation Simulator (EGOPS) software tool on which more information can be found, e.g., in [KIRC96] and [KIRC98].

4 Assessment Results and Discussion

4.1 Summary of Mission Scenarios

As a convenient reference, and as bridge from the [MISSTUD99] study to this assessment study, we recall in Table 4.1 below the main characteristics of the 39 "realistic mission scenarios" from [MISSTUD99] (summarized there in Table 5.1, in a somewhat different form). Table 4.1 is ordered by mission "Scenario No." and constellation "Case No.", respectively, and is naturally partitioned into 3 groups of 13 scenarios / 7 actual constellations, one group for each the 6-sat, the 12-sat, and the 24-sat constellations. For each constellation, the number of orbit planes (2 or 4), the number of satellites per plane (2, 3, 4, 6, or 8; e.g., "3-3" for 3 sats in each of two planes), and the inclinations of the planes (30, 40, 55, 60, 80, or 98 deg; e.g., "80-30" for one 80 deg and one 30 deg plane) are indicated. Furthermore, for each scenario, the node separation (0, 45, or 90 deg) is given. For details on these mission scenarios, the rationale behind their selection, and the performance statistics results see [MISSTUD99].

4.2 Constellation Performance Assessment

We have produced the assessment results for the 39 scenarios/21 constellations of Table 4.1, i.e., we computed all defined performance descriptors J_l ($l \,\epsilon\, \{d, c, N, \sigma_N, \sigma_d, t, \sigma_t, tot\}$) according to the description in section 3.3 above.

Scenario No.	Case No.	Orbit Planes	Satellite No.	Inclinations [deg]	Node Sep. [deg]
1	1	2	3-3	80-30	90
2					0
3	2	2	4-2	80-30	90
4					0
5	3	2	3-3	80-55	90
6					0
7	4	2	4-2	80-55	90
8					0
9	5	2	3-3	98-30	90
10					0
11	6	2	4-2	98-30	90
12					0
13†	7	2	3-3	98-98	90‡
14	8	2	6-6	80-30	90
15					0
16	9	2	8-4	80-30	90
17					0
18	10	2	6-6	80-55	90
19					0
20	11	2	8-4	80-55	90
21					0
22	12	2	6-6	98-30	90
23					0
24	13	2	8-4	98-30	90
25					0
26†	14	2	6-6	98-98	90‡
27	15	4	6-6-6-6	80-80-30-30	45
28					0
29	16	4	8-8-4-4	80-80-30-30	45
30					0
31	17	4	6-6-6-6	80-60-40-20	45
32					0
33	18	4	8-8-4-4	80-60-40-20	45
34					0
35	19	4	6-6-6-6	98-98-30-30	45
36					0
37	20	4	8-8-4-4	98-98-30-30	45
38					0
39†	21	4	6-6-6-6	98-98-98-98	45‡

Table 4.1: Main characteristics of the "realistic scenarios"/satellite constellations of the [MISSTUD99] study.

Notes: (†) For pure sun-sync cases only one scenario exists (cf. section 3.3).
(‡) For pure sun-sync cases the orbit node separation is always fixed to maximum spread.

Figure 4.1 conveniently visualizes the assessment results in a single "Satellite Constellations Performance Assessment" plot. The left-hand column shows the results for all scenarios, ordered by the "Scenario No." of Table 4.1, the right-hand column for all actual constellations, ordered by the "Case No." of Table 4.1. Each column shows the values of all eight J_l's ($l \,\epsilon\, \{d, c, N, \sigma_N = sN, \sigma_d = sd, t, \sigma_t = st, tot\}$), i.e., the seven specific penalties, J_k, and their weighted, normalized sum, J_{tot}. The J_k's themselves are shown for clarity without weighting ($J_k = F_k$) but the weighting factors f_k applied when producing the weighted sum J_{tot}, shown in the bottom subpanels, are indicated in each J_k-subpanel.

A closer inspection of Figure 4.1 is quite instructive for learning about how the different performance descriptors depend on given scenarios and particularly given constellations, and how the different descriptors add up to the final single figure-of-merit J_{tot}.

The Sampling Requirements Penalty, J_d, and the Event Number Penalty, J_N, respectively, are counteracted by the Mission Cost Penalty, J_c. This is quite expected since all these depend most sensitively on the constellation size, with the Mission Costs depending on it in a reverse manner, i.e., bigger constellations being most heavily penalized.
The Unequal Coverage Penalty, $J_{\sigma_d=sN}$, shows a less straightforward behavior, it is least penalized by constellations with some near-optimal spread in orbital planes and their inclinations.
Interestingly, the Time Separation Penalty, J_t, is roughly unaffected by total constellation size, it even shows a slight penalty increase towards bigger constellations. Apparently bigger constellations tend to slightly more intermingle in UT individual occultation events due to closer packing of satellites in space, which statistically makes neighbor events happen slightly more separated in UT.
A salient feature of the distance and time dispersion penalties, $J_{\sigma_d=sd}$ and $J_{\sigma_t=st}$, is that they are somewhat correlated in their behavior and that they tend, in particular $J_{\sigma_d=sd}$, to put relatively high penalty to constellations with most unfavorable differences between maximal node alignment and maximal node dispersion situations.

The Total Penalty, J_{tot}, exhibits comparatively flat dependence on the constellation cases, which is perhaps somewhat surprising at first glance. In other words, this single figure-of-merit does not sharply separate at a glance specific best constellations from other much worse constellations. This is not too surprising, however, considering that J_{tot} is a sum of a series of competing and mutually counteracting aspects and that we have selected a sample of 21 constellations which are already "fairly good" compared to arbitrary selections from the basin space of constellation options (cf. [MISSTUD99]). The histogram $J_{tot}(Case\ No.)$ should basically behave rather flat if not high unequal weighting is applied to stress one or very few specfic aspects J_k, which we did not consider appropriate for lack of convincing rationales.

It is nevertheless sensible, and the correct way to go based on such a quantitative assessment, to take the indication of least-penalty in $J_{tot}(Case\ No.)$ as pointing to the most favorable constellations in the candidate sample. It is the bottom-right subpanel of Figure 4.1 giving this information. As we have, according to the constraints set out in section 2, to select one case from group 1–7 (6 sats), one from 8–14 (12 sats), and one from 15-21 (24 sats), respectively, the least-penalty criterion suggests a first downselection to cases 5-7 (6 sats), 12–14 (12 sats), and 16 & 19–20 (24 sats), respectively. This were a downselection to nine cases and we can go back to Table 4.1 to see which constellations have been drawn.

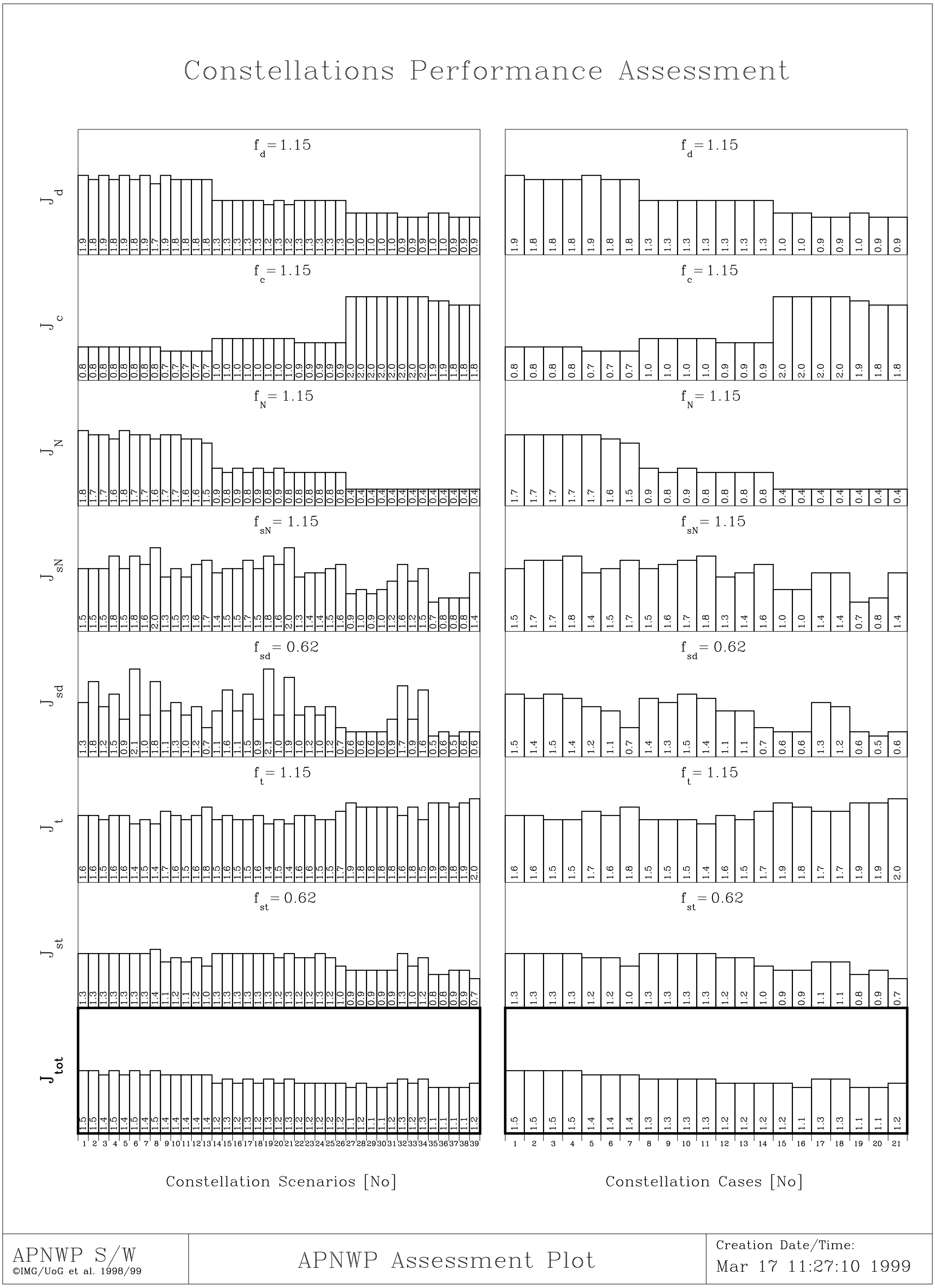

Figure 4.1: Satellite Constellations Performance Assessment.

It is important to note that somewhat different weighting might lead to a somewhat different downselection so this result on its own is certainly not sufficient decision support for a firm and final selection. More generally speaking it seems sensible to conclude from Figure 4.1 that, for each of the 3 groups (6, 12, or 24 sats), the last three cases (5–7, 12–14, 19–21) and the second case (2, 9, 16) are cases of interest for the final sample.

Since Figure 4.1, however, definitely does not lead to an unique conclusion on three constellations, we proceed, as outlined at the end of section 3 above, with invoking a performance descriptor at the next level of complexity, i.e., the "vector descriptor" $N(\varphi)$. We use $N(\varphi)$ histogram functions for an assessment refinement.

4.3 Assessment Refinement by Latitudinal Statistics

The half-way downselection to three to four cases per group performed above suggests, via checking with Table 4.1, that the cases of interest are those with 80 deg and 30 deg inclined planes and fewer satellites in the lower-inclined plane(s) (2, 9, 16), or with 98 deg (sun-sync) and 30 deg inclined planes (5, 6, 12, 13, 19, 20), or pure sun-sync cases (7, 14, 21).

We shall study these cases here closer in terms of the vector descriptor $N(\varphi)$, which we ideally expect to show independence of N on φ (equal coverage). We will discuss only the results for the "medium" group with the 12-sat constellations (cases 9, 12–14), the $N(\varphi)$ behavior of which is well representative for the other two groups with 6-sats and 24-sats.

Figures 4.2a and 4.2b illustrate the $N(\varphi)$ histogram functions for the cases of interest of the 12-sat group. The header of each panel is indicating which case/scenario is shown. Figure 4.2a shows case 9 (top panels) and case 14 (bottom panel), respectively, while Figure 4.2b shows case 12 (top panels) and case 13 (bottom panels).
Explained in more detail, the $N(\varphi)$ shown is the number of events per unit area vs. 5 deg-latitude bins as accumulated globally over 12 hours assuming that setting and rising occultations from a nominal GPS and GLONASS transmitter constellation (together 48 satellites) were collected with receiver antennae field-of-views spanning approximately $\pm$ 45 deg about the LEO orbit plane.

From Figures 4.2a and 4.2b it is obvious that $N(\varphi)$ of case 14 is the most unfavorable of all four cases. Thus we can consider this pure sun-sync case definitely less attractive than the other three cases. Furthermore, from Figure 4.2b it is seen that $N(\varphi)$ of case 12, the 98 deg/30 deg inclination case with an equal number of satellites in both planes, is less favorable than that of case 13, the 98 deg/30 deg inclination case with fewer satellites in the lower inclined plane. Thus case 12 is less attractive than case 13. Comparing, in turn, case 13 with case 9, the 80 deg/30 deg inclination case with fewer satellites in the lower inclined plane, indicates that $N(\varphi)$ of case 9 is the most favorable one of all cases considered.

We can summarize that, in terms of the vector descriptor $N(\varphi)$, the most attractive 12-sat constellation is represented by case 9 and the second best by case 13. Since the $N(\varphi)$ behavior is essentially invariant under changes in constellation size, it is justified to generalize this result by stating that the descriptor $N(\varphi)$ suggests that the final sample of constellations should either contain the 80 deg/30 deg cases 2, 9, and 16 (best choice), or the 98 deg/30 deg cases 6, 13, and 20 (second best choice). Note that both choices have one-third of all satellites in the 30 deg-plane(s).

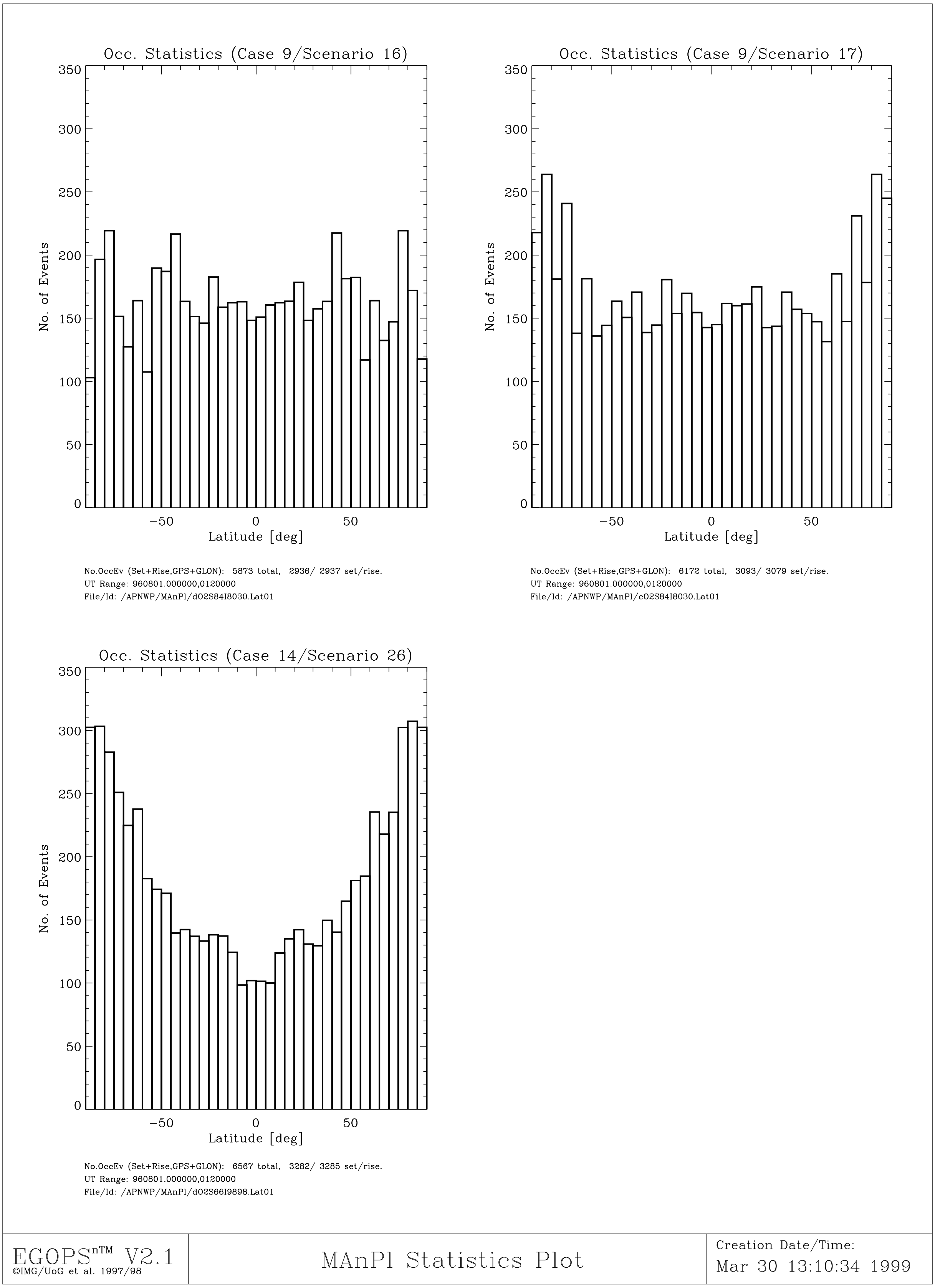

Figure 4.2a: $N(\varphi)$ histograms for constellation cases 9 and 14.

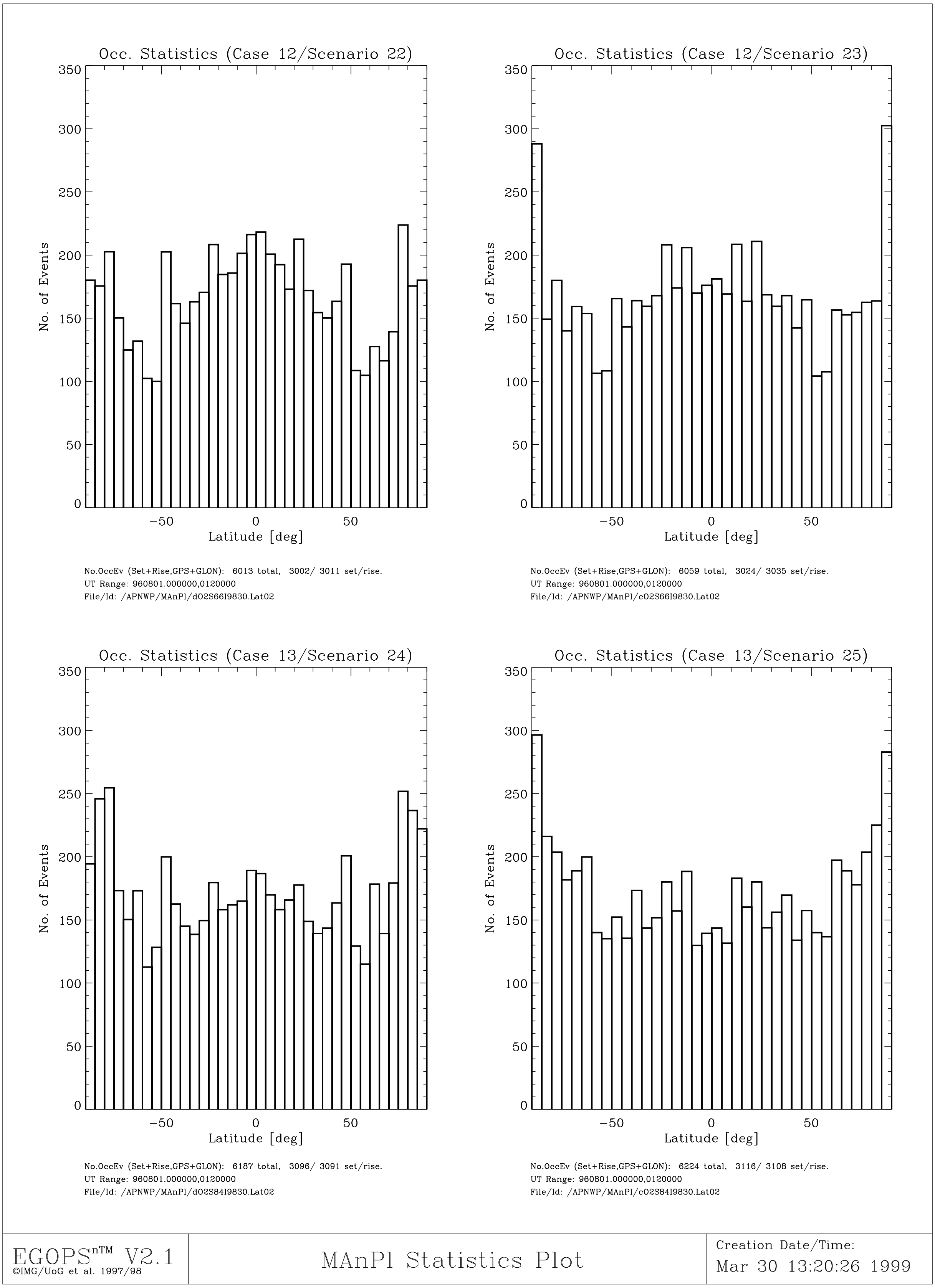

Figure 4.2b: $N(\varphi)$ histograms for constellation cases 12 and 13.

Turning back to Figure 4.1, with now focusing on cases 2/9/16 and cases 6/13/20, we see that the total performance descriptor J_{tot} suggests another order for the two choices than $N(\varphi)$: J_{tot} indicates cases 6/13/20 to be the better choice compared with cases 2/9/16. Being aware of the general limitations inherent in this quantitative assessment as decision support instrument, it seems reasonable to take this "ambiguity" as indication to keep both sets of cases for recommendation as alternative options. The relative merits of each of the options can then be discussed from an observational requirements point of view as, e.g., laid down in the [GRASSAG98] report.

5 Definition of an OSSE Study Test Mission Set

5.1 Recommendation of Two Test Mission Options

We recall that the general constraints discussed in section 1 and particularly section 2 asked for finally recommending a set, or alternative sets, of four constellations, where a set shall include one METOP/GRAS-like single-satellite case as "zero-level" baseline, one 6-sat constellation, one 12-sat constellation, and one 24-sat constellation. Given these constraints, we found via the quantitative assessement discussed in section 4 that, in the notion of Table 4.1, either the set of constellation cases 2/9/16 or the one of cases 6/13/20 should join the single-satellite case in the final sample.

Based on these results we finally recommend as OSSE study test mission set one of the two options summarized respectively in Table 5.1 and Table 5.2 below (table format as for Table 4.1). We close below with a brief discussion of Tables 5.1 and 5.2 and conclude that option 1, summarized by Table 5.1, should be defined as OSSE test mission set. Nevertheless, we recommend that a final decision on which mission set is definitely selected should be taken by group agreement in the OSSE study team at its "Simulation Plan Review" meeting (scheduled April 1999).

Scenario No.	**Case No.**	**Orbit Planes**	**Satellite No.**	**Inclination(s) [deg]**	**Node Sep. [deg]**
n/a	lev0†	1	1	98	n/a
3	**2**	2	4-2	80-30	90
4					0
16	**9**	2	8-4	80-30	90
17					0
29	**16**	4	8-8-4-4	80-80-30-30	45
30					0

Table 5.1: *OSSE test mission set, Option 1* – Baseline case & Constellations with 80 deg / 30 deg inclined orbit planes, one-third of all satellites in 30 deg plane(s).

Notes: (†) METOP-like sun-sync satellite ("zero-level" single-sat baseline).

Scenario No.	Case No.	Orbit Planes	Satellite No.	Inclination(s) [deg]	Node Sep. [deg]
n/a	lev0†	1	1	98	n/a
11	**6**	2	4-2	98-30	90
12					0
24	**13**	2	8-4	98-30	90
25					0
37	**20**	4	8-8-4-4	98-98-30-30	45
38					0

Table 5.2: *OSSE test mission set, Option 2* – Baseline case & Constellations with 98 deg / 30 deg inclined orbit planes, one-third of all satellites in 30 deg plane(s).

Notes: (†) METOP-like sun-sync satellite (”zero-level” single-sat baseline).

5.2 Discussion of Options and Preferred Mission Set

It is useful to discuss the relative merits of options 1 and 2 from an observational requirements point of view, as, e.g., set out in form of the ”Generic GRAS Observational Requirements” in chapter 4 of [GRASSAG98]. Since the OSSE study is directly related to the NWP impact of GNSS occultations one may put distinct emphasis on the ”Operational Meteorology” requirements (as found useful when setting the scene for the [MISSTUD99] study).
A somewhat different perspective were to explicitly also take care of requirements for other purposes, most importantly those of ”Climate Monitoring and Prediction”. We like to take the latter perspective since any practical implementation will certainly be one single constellation in space, which shall fulfil multiple-purpose requirements. Thus, even though we seek here an OSSE test mission set, it seems not sensible to discuss constellation options solely on the grounds of ”Operational Meteorology” requirements.

Turning to discussing the two options now, it is clear that they are fairly similar in orbital layout; the difference is just that the high-inclination planes of the constellations are prograde (80 deg) and drifting in local time for option 1, while they are retrograde and sun-sync ($\sim$98 deg) for option 2. Given this similarity it is not too surprising that our quantitative performance descriptors had difficulties to clearly favor one of these options.

One implication of the difference, though, is about 2 deg/day more differential drift between high-inclination and low-inclination planes for option 2 compared to option 1. In other words, while option 1 will take about 3 weeks (1.5 weeks for case 16) to change from maximal node alignment to maximal node dispersion, option 2 will take only about 2 weeks (1 week for case 20). Though this is interesting, it seems difficult, from the requirements point of view, to derive from this implication significantly different merits of the options.

Another implication of the difference is that the high-inclination planes are drifting in local time for option 1 while they reside at fixed local time for option 2. This implies that all high-latitude occultation events (beyond about $\pm$ 50–60 deg) of option 2 occur at fixed local times throughout the mission, which is of particular significance for the 6-sat and 12-sat cases furnishing a single high-inclination plane. For option 1 it would take about 5 months to sample all local times at high latitudes by a single high-inclination plane, providing full local time sampling about 2.3 times a year. From the requirements point of view we see a clear advantage for option 1 from this implication, particularly in case of the 6-sat and 12-sat constellations, since all requirement classes summarized in [GRASSAG98] prefer sampling of events through different local times at all latitudes. This preference is tendatively least important for operational meteorology, but very important for climate monitoring, prediction, and climatology, and crucially important for ionosphere and space weather applications. This is a strong argument clearly favoring option 1.

A non-scientific advantage of option 2 seems that the majority of the satellites are sun-sync ones which significantly reduces their costs (more simple power supply due to fixed sun angles, etc.). This were a relevant economic argument in favor of option 2. On the other hand, option 1 allows to built all satellites with an identical design – while option 2 would need both a sun-sync and a non-sun-sync type – which also is a cost reduction factor. Without further more detailed cost assessment we cannot decide on this economic question here. Since we take a requirement-oriented point of view, this is not a primary point in this context anyway, however.

From this brief discussion of the relative merits of the two options considered we conclude that we clearly prefer option 1, summarized by Table 5.1, to be the final set of OSSE study test missions.

6 References

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