RESISTANCE TO SATELLITE FAILURES OF LEO COMMUNICATION SYSTEMS

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ABSTRACT

This paper presents a satellite failure analysis for Low Earth Orbit (LEO) constellations with continuous global coverage. Worst case failure configurations are identified for polar orbit constellations and the coverage performance deterioration is evaluated by computer simulations. Then, the probability of having a number of satellite failures in a given constellation is evaluated as a function of satellite reliability. It is shown that the probability of occurence of a worst case failure configuration is very low, and that the most probable configuration is a uniform distribution of the defective satellites. As a consequence, the maximum tolerable number of satellite failures occuring simultaneously in a constellation can be determined, for a specified minimum coverage performance. Therefore, assuming a given launch delay for the replacement of satellites, one can estimate the necessary overall satellite reliability. Finally, a constellation deployment and maintenance strategy based on those results is proposed.

1. INTRODUCTION

Many recent studies have been dedicated to optimum low earth orbit constellation configurations providing world-wide communication services [1][2] & [6]-[10]. These optimum configurations can provide adequate continuous global coverage with a minimum number of satellites. However, the influence of satellite failures during system operation, resulting in coverage performance degradation, have not been investigated.

This paper identifies the worst case arrangements of defective satellites in a constellation and evaluates the resulting coverage deterioration.

In the following, a satellite failure corresponds to the complete loss of a satellite. No account is made of a partial function loss which might allow maintaining a degraded service.

The coverage performances of the constellations are evaluated by computer simulations using the LEONART[1] software [3][4].

2. FAILURE ANALYSIS

A failure analysis for polar orbit constellations providing continous single global coverage has been carried out in order to find the most unfavourable configuration for the defective satellites in the constellation geometry. Four constellations of the BESTE type [1] with altitudes ranging from about 500 to 1500 km have been examined (table 1). This altitude range is representative of LEO applications, for which minimum elevation angles of at least 10° are required. The BESTE (7,11) constellation containing 77 satellites in 7 planes is very similar to the IRIDIUM constellation, a LEO communications system concept proposed by Motorola Satellite Communications, Inc. [5].

Constel-lation	Nb. of sat.	Nb. of planes	Nb. of sat. per plane	Alti-tude (km)
BESTE (5,8)	40	5	8	1370
BESTE (6,10)	60	6	10	953
BESTE (7,11)	77	7	11	773
BESTE (9,15)	135	9	15	496

Tab. 1. Examined constellations

The worst case configuration of failures is that corresponding to the defective satellites being in adjacent positions. Indeed, such an arrangement produces the largest hole in the coverage for a given number of satellite failures. Among all the

[1] LEONART (Low Earth Orbit Numerical Analysis and Research Tools) has been developped by TELECOM Paris, Site de Toulouse, under contract with C.N.E.S., the french space agency.

possible adjacent failure configurations, two worst case configurations for polar orbit constellations have been identified by computer simulations: *longitudinal configurations* and *lateral configurations* of failures.

A longitudinal configuration of failures appears when all the defective satellites are in adjacent positions in the same orbital plane. Figure 1a shows a schematic representation of the visibility circles of a polar orbit constellation and 4 defective satellites in this configuration. Simulation results have shown that this configuration of failures corresponds to the worst coverage performance in terms of *maximum time of non-visibility*. However, this is true below a maximum latitude. Beyond, due to polar orbit convergence towards the poles, the visibility circles of satellites in adjacent orbital planes cover the missing footprints of the failed satellites.

In a lateral configuration the defective satellites are lying in adjacent planes, at roughly the same latitude. Figure 1b shows such a configuration with 4 defective satellites. Compared to the previous case, the coverage performance is degraded up to higher latitudes, but the maximum time of non-visibility is reduced.

For inclined orbit constellations, no simple rule could be found because of the influence of the inclination on the constellation topology. Hence, the worst case failure configurations have to be determined for each specific case.

Computer simulations have been carried out for the constellations in table 1 and for both longitudinal and lateral failure configurations.

. Figure 2 shows the simulation results in terms of maximum time of non-visibility for the BESTE (7,11) constellation and longitudinal failure configurations. The number of satellites failures occuring simultaneously ranges from 0 to 11, which corresponds to the loss of all the satellites in an orbital plane. In this case, the maximum waiting time reaches a value of approximately 1 h 20 mn. One can see that it is the highest at the equator and remains more or less at this level up to a latitude of approximately 45 degrees. Beyond this latitude, the overlapping of the coverage by satellites in adjacent orbital planes results in a drastic reduction of the maximum time of non-visibility and the number of failures is no longer of influence.

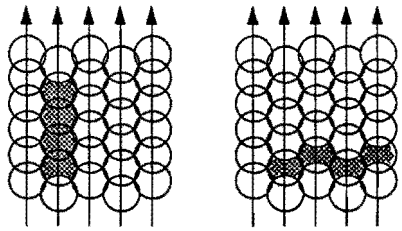

Fig. 1 - Worst case failure configurations in polar orbit constellations: (a) longitudinal, (b) lateral

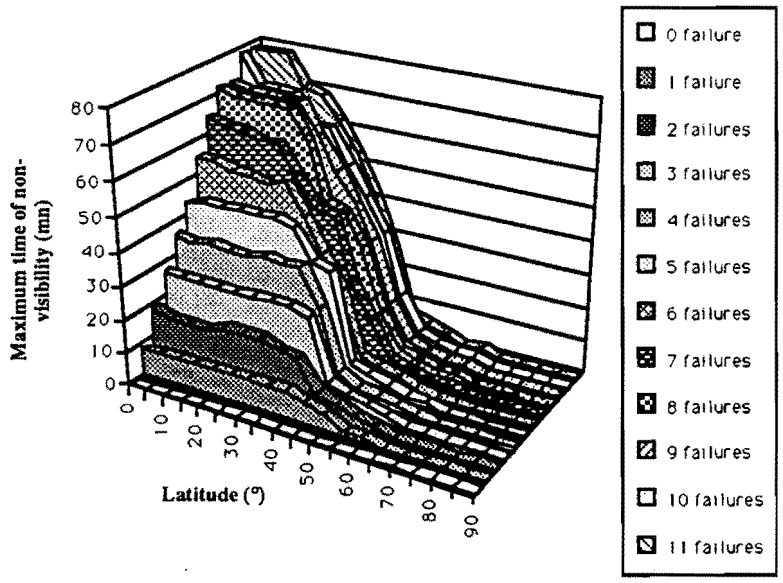

Fig. 2 - Simulation results for the Beste (7,11) constellation and longitudinal failure configurations

On the contrary, considering lateral failure configurations, the influence of the holes in the coverage reaches higher latitudes. Figure 3 shows the simulation results for the same BESTE (7,11) constellation with up to 7 satellite failures. The maximum number of 7 failures corresponds to a 'belt' of defective satellites round the globe. In this case, the coverage deteriorates up to a latitude of 90°. The maximum time of non-visibilty reaches about 10 minutes for two failed satellites and this value does not increase with a higher number of failures (Cf. Fig. 3 (a)).

Comparing figures 2 and 3 (a), the maximum time of non-visibility of lateral failures configurations is far less important than for longitudinal configurations, with equal number of failures. However, the *mean time ratio of visibility*, defined as the percentage of time when at least one satellite is visible, is a more significant criterion for lateral failures configurations.

Figure 3 (b) shows the mean time ratio of visibility as a function of latitude and of the number of lateral satellites failures for the BESTE(7,11) constellation. This coverage performance criterion decreases when the number of failures increases. This means that the service interruptions, in the case of lateral failure configurations, are shorter and more frequent than in the case of longitudinal failure configurations.

The fact that the affected latitudes are higher for lateral configurations than for longitudinal ones is not of importance. Indeed, the latitudes are affected up to 50° for longitudinal configurations, and this does not fit coverage requirements for services over Europe or the United States.

For these reasons, in the following, the longitudinal failure configurations are considered as worst case configurations.

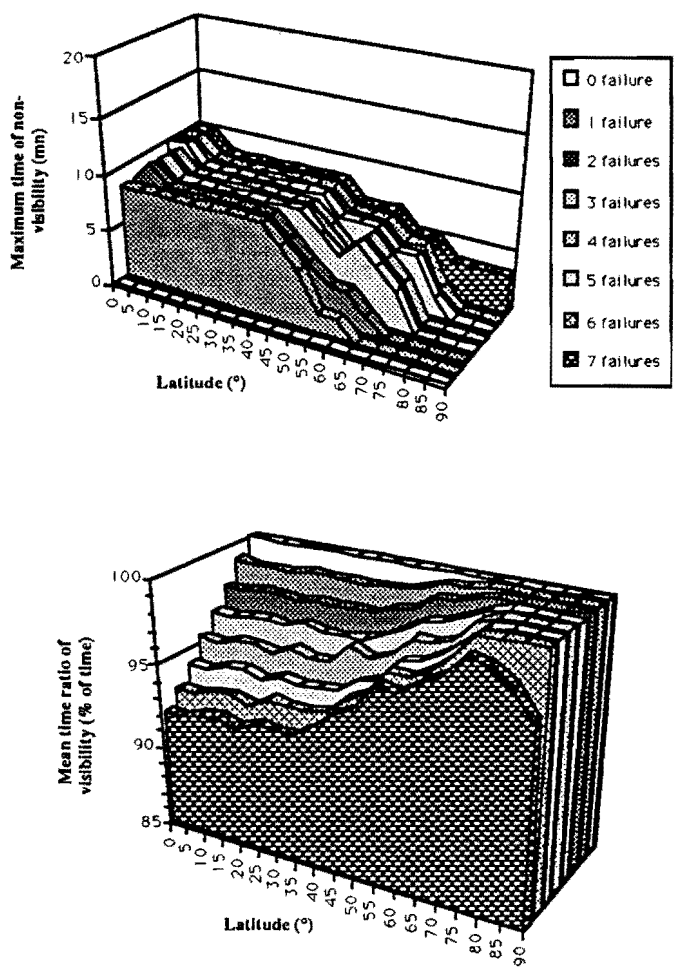

Fig. 3. Simulation results for the Beste (7,11) constellation and lateral failure configurations: (a) Maximum time of non-visibility, (b) Mean time ratio of visibility

A comparison of the results for the constellations of Table 1 is displayed on Figure 4 and 5 for longitudinal configurations of failures and on Figure 6 for lateral configurations of failures.

Figure 4 shows the maximum time of non-visibility for a user located at the equator, which is the worst possible user position, as a function of the number of satellite failures. The maximum time of non-visibility is lower for constellations with a larger number of satellites (and then lower altitudes) for the same number of satellites failures.

Figure 5 shows as an example the maximum time of non-visibility produced by the loss of 4 satellites in a longitudinal configuration as a function of latitude. The latitude beyond which the degradation of coverage is negligible is about the same for all constellations (45° to 50°).

Figure 6 shows as an example the maximum time of non-visibility produced by the loss of 4 satellites in a lateral configuration as a function of latitude. Compared to the previous curves, the maximum time of non-visibility does not exceed 15 minutes against 55 minutes. On the other hand, the latitude beyond which the service is continuously available is over 70°, and this for all constellations.

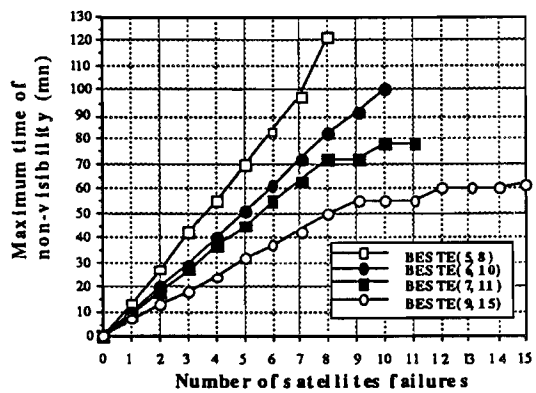

Fig. 4 - Longitudinal configuration of failures: Maximum time of non-visibility as a function of the number of failures (for a user located at 0° latitude)

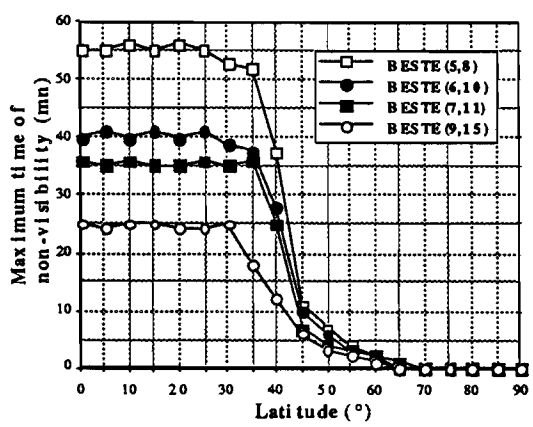

Fig. 5 - Longitudinal configuration of 4 failures: Maximum time of non-visibility as a function of latitude.

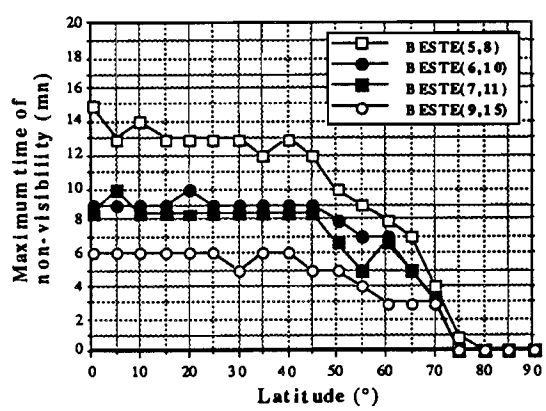

Fig. 6 - Lateral configuration of 4 failures: Maximum time of non-visibility as a function of latitude.

3. FAILURE PROBABILITY

After having identified the worst case configuration of failures, the probability of having a number of defective satellites in a constellation has been determined. This probability depends on the satellites reliability and on the satellites life time. During the operation phase, the failure rate of satellites is considered as constant. So, the failure probability of one satellite can be calculated as a function of the duration of operation t and the MTBF (Mean Time Between Failures):

$$d = 1 - e^{-t/MTBF} \qquad (3.1)$$

The occurence of failures in a satellite constellation follows a binomial law. For a certain satellite failure probability d, the probability of having at least k defective satellites in a constellation containing T satellites is given by the following expression:

$$P_{k1} = \sum_{i=k}^{T} \binom{T}{i} \cdot d^{i} \cdot (1-d)^{T-i} \qquad (3.2)$$

The probability of occurence of at least k failures in a constellation of 77 satellites is shown in Figure 7 as a function of the normalized duration of operation $\tau = t/MTBF$. Assuming that the lifetime of the satellites is identical to their MTBF the diagram shows that at the end of life, which corresponds to $\tau = 1.0$, one can expect 40 satellite failures with a probability of about 100%.

It has been shown earlier that the worst case in terms of maximum waiting time is a longitudinal configuration of failures. The probability of occurence of such a configuration has also been determined:

$$P_k = \frac{T}{\binom{T}{k}} \cdot \sum_{i=k}^{T} \binom{T}{i} \cdot d^{i} \cdot (1-d)^{T-i} \qquad (3.3)$$

It is noteworthy that this probability does not depend on the number of planes and satellites per plane, but only on the total number of satellites.

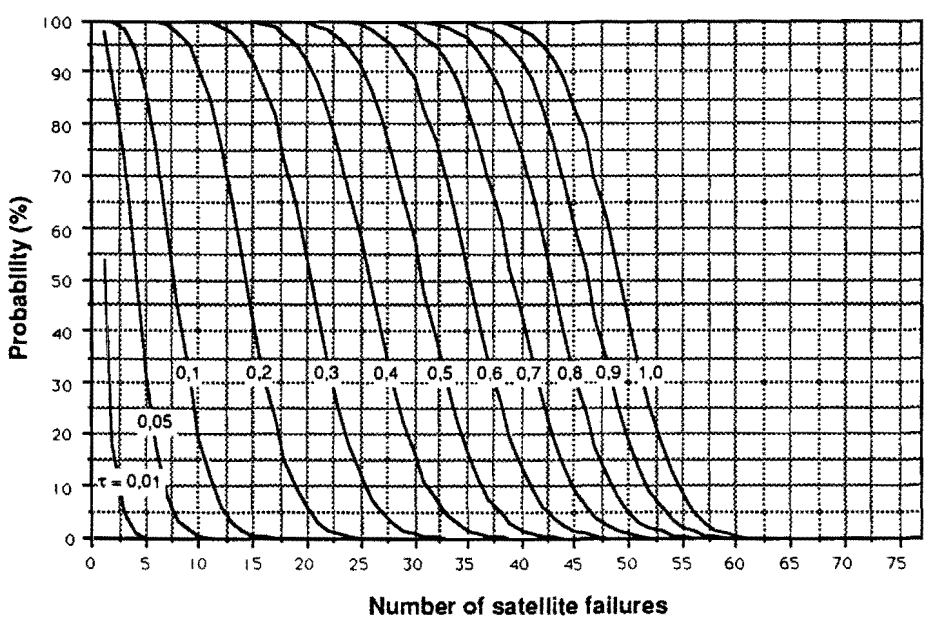

Fig. 7 - Probability of ocurence of at least k satellite failures in a constellation containing 77 satellites

Figure 8 shows the probability of having a given number of failures, at the end of life, in a longitudinal configuration for the examined constellations. This diagram shows that the occurence of such a configuration is very unlikely. For two adjacent defective satellites, in the same orbital plane, the probability for the smallest constellation (40 satellites) is about 5 %. For greater constellations (in terms of number of satellites), this probability decreases even more. For higher number of failures, the values go down rapidly and the occurence of a longitudinal configuration with 4 or more satellites can be neglected.

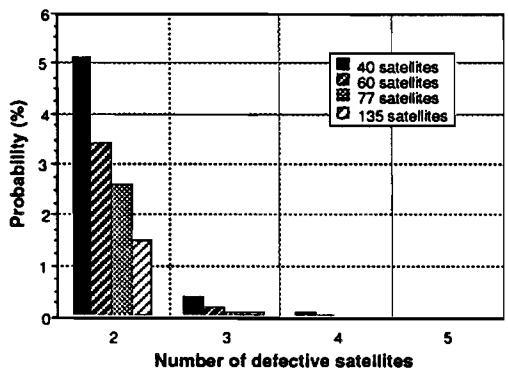

Fig. 8 - Probability of occurence of a number of satellite failures in longitudinal configuration, at the end of life (τ=1)

These results show that the occurence of a longitudinal failure configuration is very unlikely. Hereafter in the case of more than one satellite failure in a constellation, it is more probable to have them randomly distributed in non-adjacent positions.

Therefore, the degradation of coverage performance due to the occurence of a longitudinal configuration of failures is not a key feature for the design of a constellation.

4. COVERAGE PERFORMANCE

As a consequence of these results, it is more suitable to use the *mean time ratio of visibility* in order to characterise the coverage degradation due to non-adjacent and randomly distributed satellite failures. This can be evaluated exactly by computer simulations for any constellation topology. However, for polar orbit constellations, an analytical approximation can be established to evaluate the mean time ratio of visibility.

Indeed, imagine that the constellation orbital planes are fixed and that the earth is rotating underneath: a user crosses the same orbital plane twice a day. So, in the worst case, he crosses a hole in the coverage produced by a defective satellite twice every 24 hours . The mean time ratio of visibility R is then:

$$R = 1 - k \cdot \frac{2\,T_1}{24 \text{ hours}} \qquad (4.1)$$

where k is the number of satellite failures ocurring simultaneously and T_1 the average waiting time produced by a single failure. The single failure average waiting time T_1 can be approximated for polar orbit constellations. Equation (4.2) gives T_1 as a function of the orbit period T_{orb}, the number of satellites per plane m and the coverage angle of the satellites Ψ.

$$T_1 = T_{orb} \cdot \left(\frac{2}{m} - \frac{\psi}{180°}\right) \qquad (4.2)$$

The angle of coverage can be expressed as a function of satellite altitude H, minimum elevation angle ε at users location and earth radius R_E:

$$\psi = \operatorname{acos}\left(\frac{R_E \cos \varepsilon}{H + R_E}\right) - \varepsilon \qquad (4.3)$$

The results of this worst case approximation have been confirmed by the simulations of coverage performance for the constellations described in Table 1. Table 2 shows a comparison between simulation results and results from (4.2). The maximum difference between the approximated and simulated results is about 1 minute.

Constellation	Simulation	Approximation
BESTE (5,8)	12,5	11,5
BESTE (6,10)	6,8	8
BESTE (7,11)	8,25	8
BESTE (9,15)	5,75	5

Tab. 2. Single failure average time of non-visibility (minutes)

For constellations using inclined orbits, the average waiting time produced by a single failure can be determined by computer simulations.

This method enables estimating the coverage performance of a given constellation in terms of mean time ratio of visibility as a function of the number of non-adjacent satellite failures occuring simultaneously.

5. RELIABILITY AND MAINTENANCE OF A CONSTELLATION

The main goal during the operation of a constellation is to preserve the communications service the system is designed for. The coverage quality performance required for a given service can be expressed by a minimum mean time ratio of visibility, according to previous results.

The *reliability* of a constellation can be defined as the probability that this minimum coverage criterion is satisfied.

In order to keep the necessary coverage performance, even during the occurence of satellite failures, the maintenance policy and the satellites reliability have to be designed accordingly.

From the desired coverage performance and the launching capabilities an estimation method for the required satellite reliability of a constellation have been set up. The maximum tolerable number of satellite failures in a constellation, k_{max}, can be estimated from equation (5.1) given a minimal mean time ratio of visibility R_{min}:

$$k_{max} = \frac{24\ h}{2\ T_1} \cdot \left(1 - R_{min}\right) \qquad (5.1)$$

The principle of occasional maintenance has been assumed, i.e. a spare satellite is launched when a satellite in the constellation fails.

The time from the occurence of the failure to the start of operation of the replacing satellite is called the *replacement delay* of a satellite. It mainly depends on the launch rate of the available launch vehicles.

It may be that during this replacement delay failures of other satellites occur. As a consequence, the reliability of the satellites has to be sufficient to ensure that the number of failures does not exceed the maximum number k_{max}. So, the number of potential satellite failures that can occur during the replacement delay has to be estimated.

This can be achieved using equation (3.2), which gives the number of satellite failures that can occur in a constellation with a given probability after a given operation time.

Thus, for a given maximum number of satellite failures and a given replacement delay, the required MTBF of one satellite can be estimated with the equations (3.1) and (3.2).

A graphical resolution of this system of equations is proposed, using the type of diagram displayed on figure 7 for a constellation of 77 satellites. For a given maximum number of satellite failures k_{max}, and for a probability approaching 100%, the normalized duration of operation $\tau = t/\text{MTBF}$ can be read from the diagram. Then, the required MTBF of the satellites can be computed as a function of the replacement delay:

$$\text{MTBF} = \frac{T_{replacement}}{\tau} \qquad (5.2)$$

Table 3 gives the results for the examined constellations for two different minimum values of the mean time ratio of visibility R. The required MTBF for a mean time ratio of visibility of 98% and an estimated replacement delay of 2 months ranges from 3.1 years to 12.3 years.

Constel-lation	R (%)	k_{max}	τ	MTBF (years)
BESTE	95	3	0,14	1,3
(5,8)	98	1	0,06	3,1
BESTE	95	4	0,12	1,5
(6,10)	98	1	0,04	4,6
BESTE	95	4	0,09	2,1
(7,11)	98	1	0,03	6,2
BESTE	95	6	0,07	2,6
(9,15)	98	2	0,015	12,3

Tab. 3. Approximated satellites reliability required for a given mean time ratio of visibility and a replacement delay of 2 months

6. DEPLOYMENT AND MAINTENANCE STRATEGY

The methods proposed in section 5 can be useful for the preliminary design of the satellites of a constellation during the early phase of the system design.

Figure 9 illustrates a deployment and maintenance strategy for a constellation by relating the important design parameter links during the deployment and the operation phases.

The deployment and maintenance process starts from the technical service specifications and cost specifications that are to be met to provide a communications service using a LEO constellation.

Concerning the deployment phase, the maximum deployment delay and the satellites technical characteristics are the driving design parameter which influences mainly the selection of a launch vehicle. During the launcher selection, the trade-off between simple and multiple satellites in orbit placement is to be examined. Finally, the launch planning is to be established and compared to the desired deployment delay. Once performances match the specifications, the total deployment cost can be estimated.

During the operation period, a minimum coverage performance is required to keep the service. Expressed in terms of the mean time ratio

of visibility, that makes it possible to estimate the maximum number of satellite failures and then the required MTBF of the satellites which ensures a minimum coverage performance. The potential number of failures which occur until the end of life can be evaluated, which gives en estimation for the maintenance requirements of the constellation. Finally, the maintenance cost of the constellation can be estimated.

The overall cost of the system including the satellites development, the deployment and the maintenance phases can then be evaluated and compared to the cost specifications. During this process, several feedbacks loops are necessary in order to fulfill all the constraints.

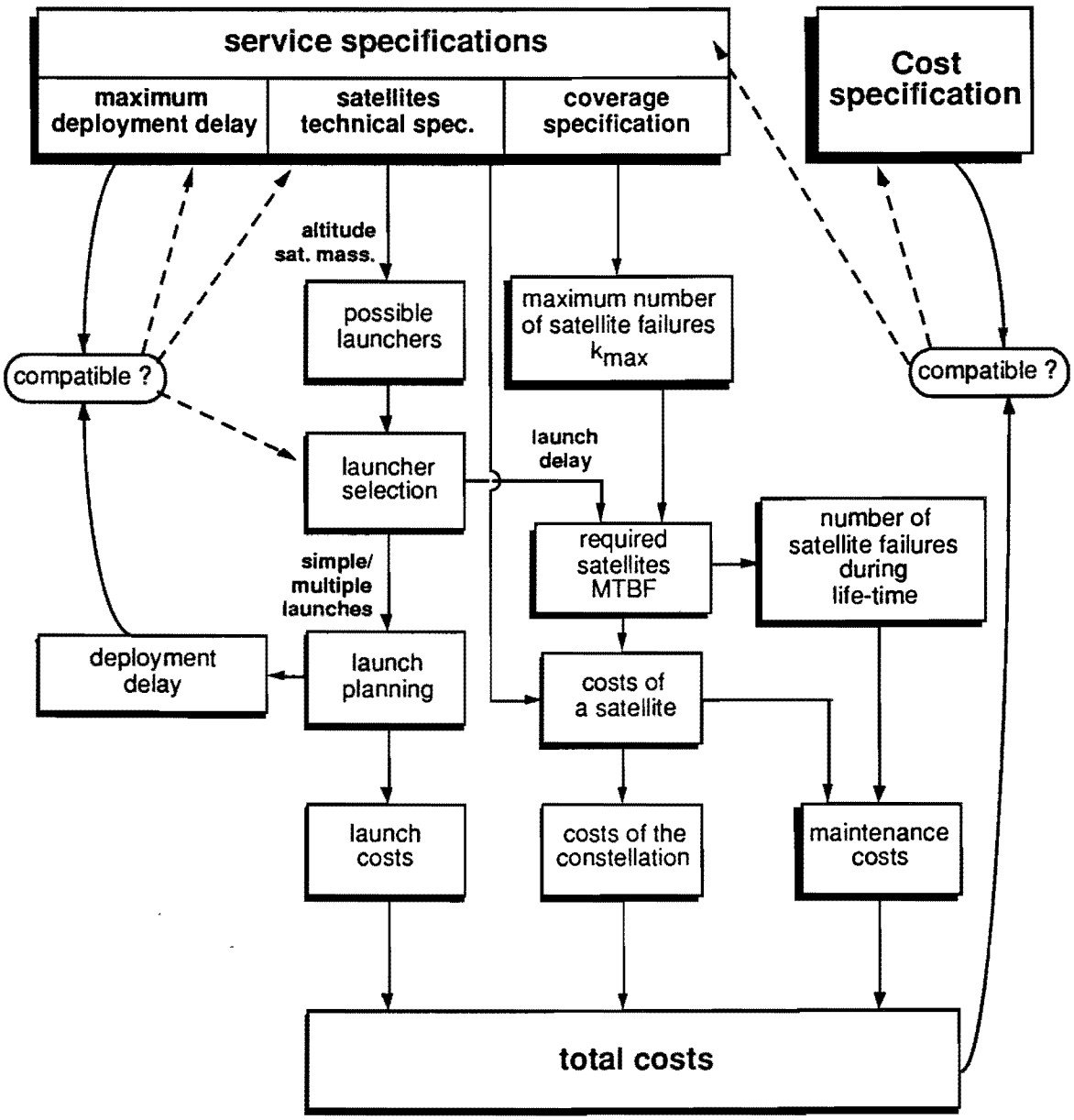

Fig. 9. Typical deployment and maintenance process

CONCLUSION

A failure analysis for polar orbit constellations has been carried out. It has been shown that the worst case configuration of satellite failures for the coverage degradation in the constellation topology is a longitudinal one. In such a configuration, all the defective satellites are in adjacent positions in the same orbital plane. An evaluation of the failure probability in a constellation has shown that such a configuration is unlikely. It is much more probable to have a distribution of defective satellites in non-adjacent positions. Moreover, the number of failures during the lifetime of the satellites of a given constellation has been estimated.

To characterize the coverage degradation due to the non-adjacent failures, the criterion of mean time of non-visibility has been used. This criterion can be approximated analytically for polar orbit constellations. For the constellations using inclined orbits, it can be evaluated with computer simulations.

An estimation method for the satellites reliability which is required to ensure a minimum coverage performance has been established.

A deployment and maintenance process has been set up relating the key parameters of minimum deployment delay, the potential launch vehicles and the required coverage performance.

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