"SPACE EGGS"

Satellite Coverage Model for Low Earth Orbit Constellations

by

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Abstract

The effectiveness calculations of global, regional, and area coverage for proliferated small satellite constellations in low altitude orbits stress the capability of conventional analytical techniques. A new approach that combines the Mollweide (equal area) projection with an on-screen color manipulation of the picture elements (or pixels) has been developed and utilized over the past decade. This technique enables the optimization of large satellite constellations with multiple communication or sensor viewing configurations, with a minimum number of calculations. Complex viewing geometries are well adapted with this analytical approach, along with exclusion requirements such as the sun, moon or earth avoidance. This technique has proven useful in minimizing the number of low altitude communication satellites (for any planet) and optimizing the sensor suite for specific missions.

I. COVERAGE ANALYSIS: WHY DO WE NEED IT and HOW IS IT DONE?

Networks or constellations of satellites offer many services and capabilities not achievable by other means. The ability to navigate ships around hazards is provided by satellite triangulation [1]. Global communications is another example of a constellations utility, where satellite networks enable two people on opposite sides of the planet to speak with each other. Surveillance programs may require continuous imaging of an entire planet, which is impossible from just one satellite. A constellation of orbiting sensors is required to perform this task. Finally, proposed weapon systems are required to counter threats from any place on the earth. Since weapons have a limited reach, only multiple weapon platforms orbiting the earth can meet this requirement (Figure 1).

Satellites in orbit about a planet are able to view a finite area (footprint) with their payloads, like a flashlight beam shining on a ball (Figure 2). As the satellite travels in an orbit around the planet, the footprint moves with it. However, if the entire planet needs to be continuously illuminated, the challenge is to determine the minimum number of orbiting "flashlights" required. Any solution other than the minimum required is unacceptable since added costs will be incurred, typically amounting to hundreds of millions of dollars. The analytical methodology used to determine a constellation's capability is known as coverage analysis, and has been studied since the 1960's [2].

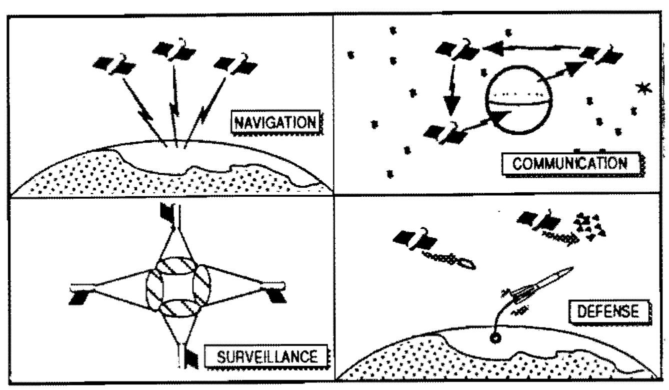

Figure 1: Networks of Satellites Offer Unprecedented Services

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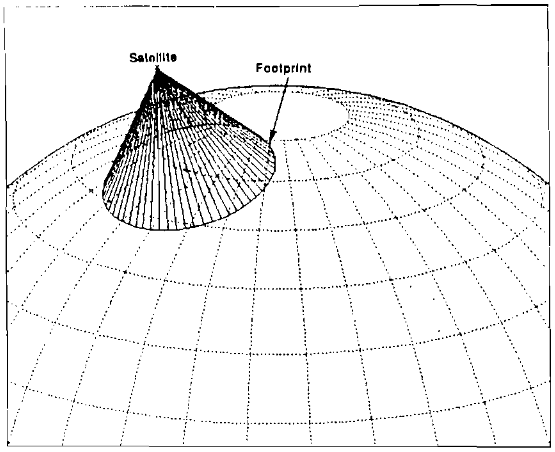


Figure 2. The Footprint is Formed by the Payloads' Viewing Characteristics

The area of a sphere covered by a satellite's footprint is a measurement of a constellation's proficiency (or percent coverage). Simple geometric footprints are easy to analyze, but difficulty grows as footprints become more complex or intertwined (Figure 3). Understanding the relationship between coverage and satellite placement is the key to optimizing a satellite constellation. In addition, this problem is compounded with the resurgence in developing small satellites and launch systems. Because of advances in miniaturization technology, several programs consisting of hundreds of satellites in low earth orbit have been proposed.

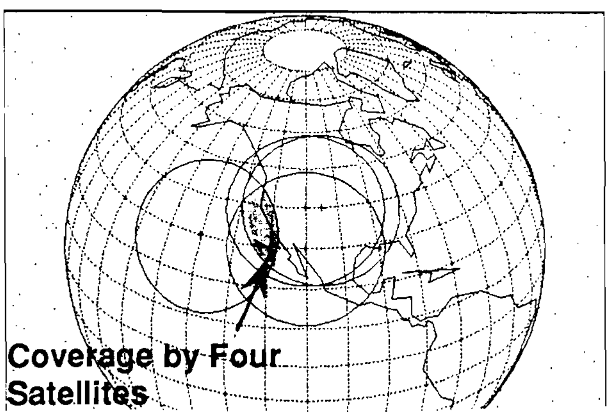


Figure 3. Calculating the Coverage from Interweaving Footprints is a Challenge

There are many variables involved in developing a constellation, which can be broken down into three primary categories (Figure 4). Programmatics will determine the coverage requirements, which can range from continuous global coverage by at least one satellite to intermittent regional coverage by multiple satellites. The payload capabilities (and technology) dictate the footprint, and can consist of range limitations, azimuthal or elevation restrictions, operating conditions, etc. The only optimization parameters available are the number of satellites, their spacing, and the respective orbital parameters.

Sizing a constellation is an iterative process since no closed form solutions exists that considers all of the variables. Coverage analysis is well suited for computers, and this paper will describe a computer program known as SPACE EGGS that can accurately and quickly determine the coverage from a set of satellites. The computational speed enables the optimization of the number of satellites required for any specific mission.

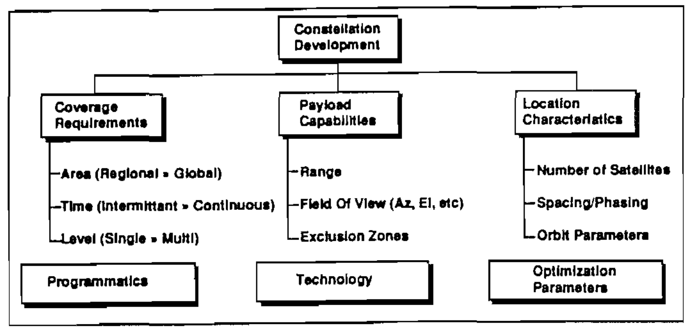


Figure 4. Developing Constellations is a Multi-Variable Operation

II. DIFFICULTIES WITH CURRENT APPROACHES

Analyzing and designing constellations has been a popular subject for many decades, and there is a wealth of information available [2-13]. Most notable is the pioneering work by J. G. Walker, who developed semi-analytic techniques based on geometric patterns [3, 13]. To give an example of satellite coverage variability, Walker developed a five (5) satellite constellation that provides continuous, global coverage from at least one satellite (single coverage), as well as a seven (7) satellite constellation providing continuous, double, and global coverage.

Others such as Ballard, Rider, and Beste developed similar semi-analytical techniques based on different coverage requirements [2-6, 9, 11-13]. For example, a constellation that provides continuous regional coverage is different than one providing continuous global coverage. These efforts are variations on Walker's work, and assume simplified constraints, at best. For example, Walker constellations have an eccentricity of zero with no payload viewing restrictions.

The first application of an eccentric orbit constellation is the Soviet Molniya communication satellites. These constellations can fully cover high northern latitudes while requiring much less launching energy than circular high-altitude orbits. Recently, Draim patented a constellation consisting of four satellites, one less than Walker's solution, that provides continuous, global coverage [8,15]. However, Draim's highly elliptical and large period (>27 hours) constellation has few practical applications for small satellites.

As payload capabilities change (such as range-limited weapon platforms), or as orbit constraints are imposed (such as the Pegasus launch vehicle capability), the previous semi-analytical techniques become more difficult to use. To compensate for the lack of analytic methods and large number of variables (Figure 4), other techniques have been developed that aid in coverage analysis: these are the use of geometry and a grid pattern.

The geometrical technique of calculating the percent a sphere is covered with a symmetrical footprint is a trivial matter. Multiple, intersecting footprints are more challenging to calculate, but mathematical techniques exist to arrive at an answer. Difficulties arise when the footprints and orbital parameters become complex, especially if satellite perturbances (such as an oblate earth) are to be considered. In fact, Draim's constellation is based solely on geometry, which probably explains why the constellation does not provide continuous global coverage of the earth over an orbital period.

To alleviate this challenge, the sphere is divided into a grid at even increments. After modeling the payload's viewing parameters and projecting them onto the sphere, the program checks the center of each grid point to determine whether that point is within the satellites' footprint. After projecting all footprints and storing the visibility data, the program calculates the percent coverage. This technique has two severe problems. The first problem is the large number of calculations required, which entails over 54,432 calculations for a sphere divided into five degree increments (36x72 points), along with a constellation of 21 satellites. Over 39 million calculations occur if the orbit period were twelve hours long with a resolution of one minute intervals. Such calculations are not a trivial task.

The second problem is the lack of fidelity involved. Footprints that enter into a grid without crossing the center are not registered during the area coverage calculations (Figure 5). Increasing the grid resolution would induce more calculations; a factor of five in resolution equates to a factor of 25 in calculations. Until recently, this problem appeared insurmountable with personal computing systems.

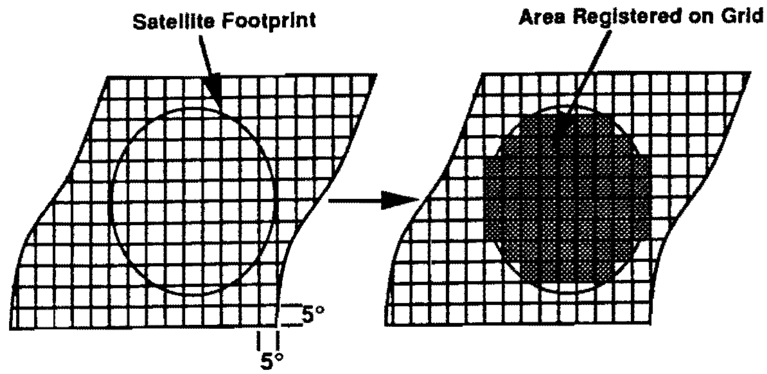


Figure 5. Fidelity is Lost with Coarse Grids

III. THE NEW APPROACH

The issues of accuracy and quickness are conflicting: highly accurate programs tend to be slow and cumbersome. Optimizing satellite constellations and their payloads is a challenge, especially as payload capabilities fluctuate during the design process. Success came with advances in computing hardware, which modified existing approaches to achieve unparalleled efficiency.

The grid technique is recognized as an accurate means to calculate the coverage capability of a satellite constellation. In addition, advancements in personal computing hardware yielded monitors rivaling the resolution in some of the best video equipment. The product of these two entities is a computer program known as SPACE EGGS, which reduces the grid to the monitor's picture elements or pixels. The program uses built-in graphic storage commands to eliminate the need of checking each pixel for satellite visibility; coverage calculations are made by determining the number of filled pixels on the screen. Since the program reads footprint areas directly off the screen, an accurate display of a three-dimensional sphere onto a two-dimensional screen is required. This is accomplished with the Mollweide projection. On this projection, a 100x100 pixel area on the screen will always represent the same area on a sphere whether the projection is at the poles or at the equator.

The combination of these unique facets provides two outstanding capabilities. First, the resolution, and hence accuracy is unmatched in comparison to the previous techniques, since the grid cannot be reduced below the pixel level.

The second capability is the sheer speed with which coverage calculations can be made, and the technique works as follows. After the payload's characteristics are modeled in the program, the satellite's footprint is superimposed onto the Mollweide projection where it is stored (Figure 6). After all satellite footprints are calculated and stored, the program recalls all stored projections. Each pixel is labeled as a variable with zero (or white) as the starting value. As the footprints are overlaid onto the screen, the color of the affected pixels are changed by one value. Thus if six (6) footprints are superimposed onto the same area, the pixel color for that area would be six. With all of the stored projections on the screen, the program checks each pixel color, line by line, storing the statistical data for each color. The percent of each pixel color is identical to the percent coverage by that many satellites. For example, a pixel color of one (1) equals coverage by one satellite, whereas a pixel color of three (3) equals coverage by three satellites (Figure 7). Program quickness is achieved since very few calculations are actually made. After characterizing the footprint, the program superimposes views and stores the graphics. When completed, the program calculates statistics based on the pixel colors that are read directly off the screen.

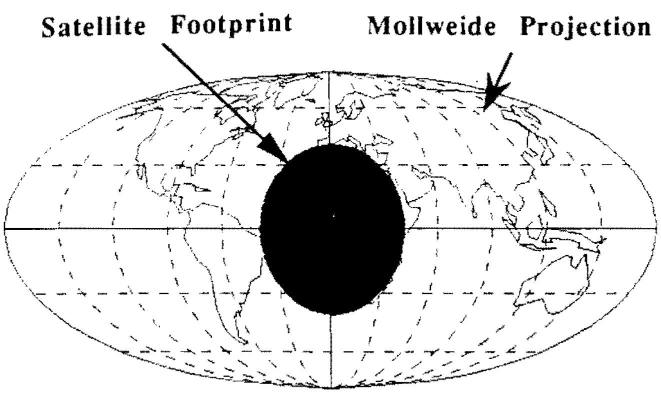


Figure 6. Individual Satellite Footprints are Superimposed onto the Mollweide Projection

Since coverage analysis is an iterative, or semi-analytic process, the program can be set up to systematically search through different constellations until arriving at a solution. The program can also quickly calculate the coverage variability as the satellites are propagated in their orbit. Orbits can be eccentric, and the addition of third body ephemeri can be used to consider cases in which solar/lunar exclusions apply. The program has also been modified to account for many different factors, such as:

* The effects on coverage of a decaying or perturbed satellite
* Coverage analysis for other bodies [14]
* Satellite-to-Satellite coverage
* Coverage from multi-sensor platforms (e.g., Earth Observation System)
* Coverage due to the loss of satellite elements (e.g., survivability)
* Coverage from Walker, symmetrical, or random constellations
* Regional coverage

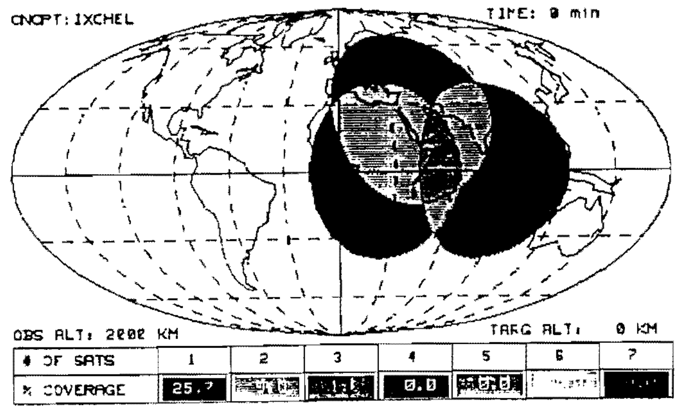


Figure 7. As Each Footprint is Recalled, the Affected Pixel Changes Color by One Value, and the Percent Coverage is Found by Summing the Pixels of Each Color

IV. APPLICATION EXAMPLES

PAYLOAD CHARACTERISTICS

Payload characteristics determine how the coverage footprint will appear on the projection, and Figure 8 shows the effect of some common payload parameters. For a given set of payload capabilities, below the horizon sensors are able to cover much more area than sensors which look above the horizon. Restricting the range or azimuth also effects the footprint size.

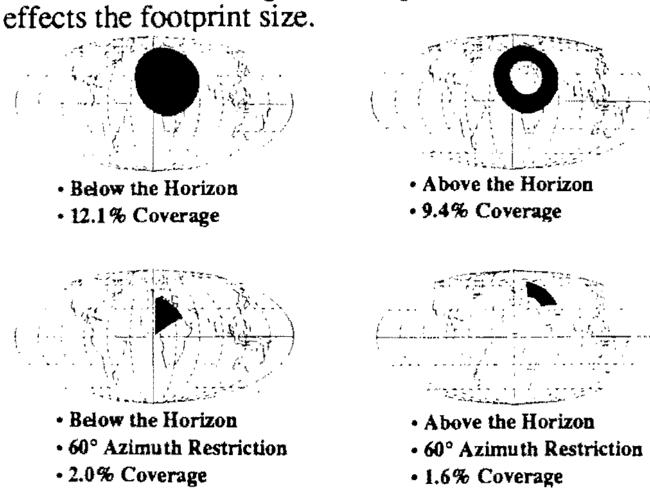


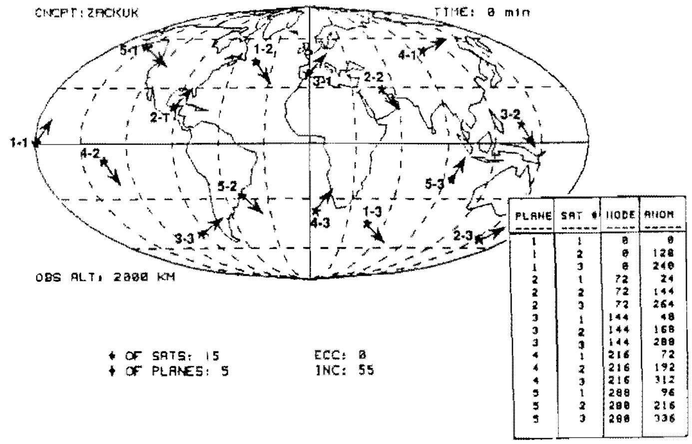
Figure 8. Payload Characteristics Determine the Footprint Pattern

SAMPLE CASES

Two examples are given. The first example is designing a constellation based on a hypothetical surveillance mission to provide continuous global coverage. The second example is a demonstration on how important sensor range is to the constellation designer. The altitude is fixed at 2000 km.

EXAMPLE I

The projected footprint for this payload is shown in Figure 6. In order to provide coverage at the equator, a minimum of five (5) planes is required, and to cover the poles, an inclination greater than 50° is necessary. In a matter of minutes, SPACE EGG's develops a solution that satisfies the coverage requirements. Relative phasing of satellites is optimized to yield a constellation consisting of 5 planes with 3 satellites per plane (15 satellites total), and an inclination of 55 degrees. Figure 9 shows an instantaneous "snapshot" of the satellites' positions, and Figure 10 displays the coverage for this constellation at that time. Coverage capability over time for this constellation is shown in Figure 11 (duration is the time it takes for one satellite to shift into another satellite's position).



PLANE	SAT #	NODE	ANOM
1	1	0	0
1	2	0	120
1	3	0	240
2	1	72	24
2	2	72	144
2	3	72	264
3	1	144	48
3	2	144	168
3	3	144	288
4	1	216	72
4	2	216	192
4	3	216	312
5	1	288	96
5	2	288	216
5	3	288	336

Figure 9. The Result of SPACE EGGs is a 15 Satellite Constellation, whose positions are shown

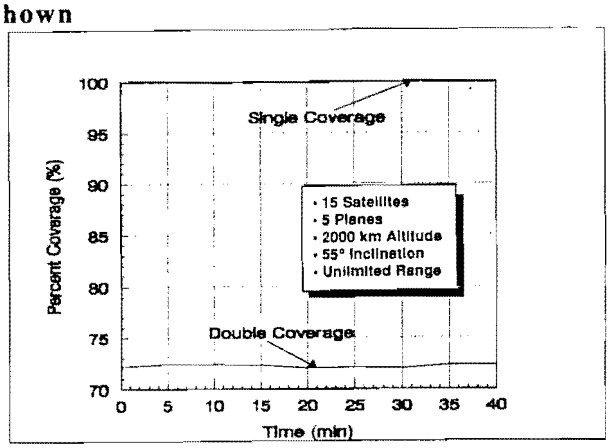


Figure 11. Coverage Over Time

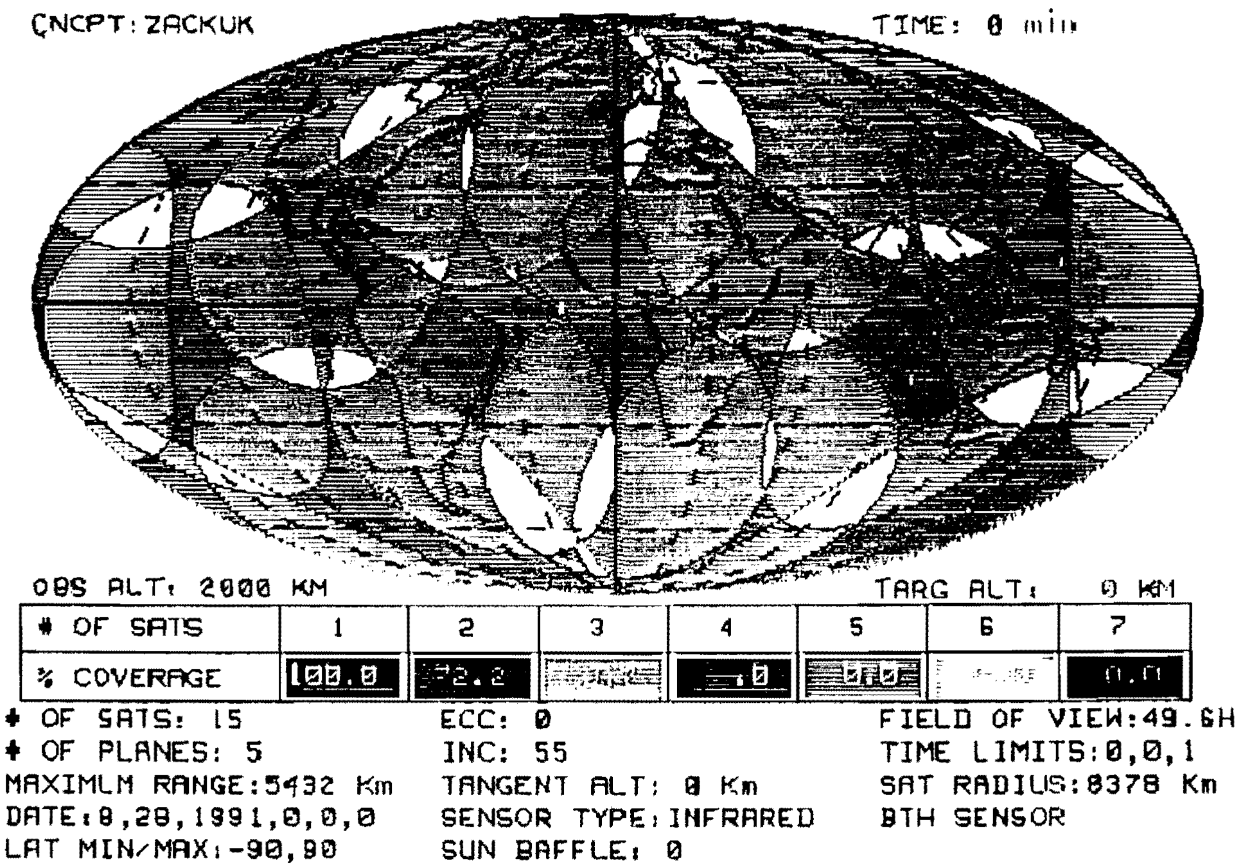


Figure 10. Instantaneous Coverage From SPACE EGG's

EXAMPLE II

The second case considers a sensor with a limited range, and will show a drastic effect on the coverage capability. Figure 12 displays the new coverage for the same conditions as before, yet with a maximum range capability of 4,500 km. Note how single coverage is reduced to 86.1%. To make up for the loss of coverage, the program is allowed to search iteratively in satellite inclination, phasing and total number of satellites. This search yields a constellation inclined at 59°, with 23 planes and 1 satellite per plane (23 satellites total). Figure 13 represents the instantaneous positions, and Figures 14 and 15 depict the coverage characteristics for these new parameters.

V. SUMMARY

SPACE EGGS is shown to reduce coverage analysis to a manageable level with current personal computers. This is made possible with advances in computing hardware, specifically the color monitors on personal computers. The program can model all variables associated with coverage analysis, along with performing multi-variable searches to arrive at a minimum constellation size for any set of requirements.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to the many analysts since 1980 who have greatly contributed to the development of many aspects within this program.

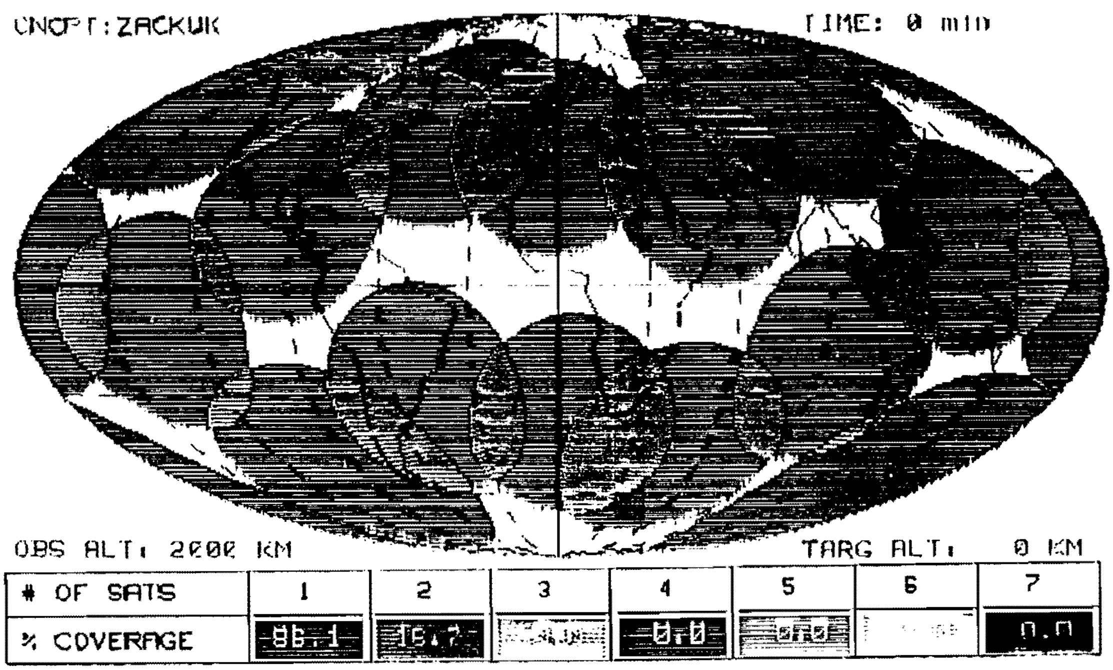
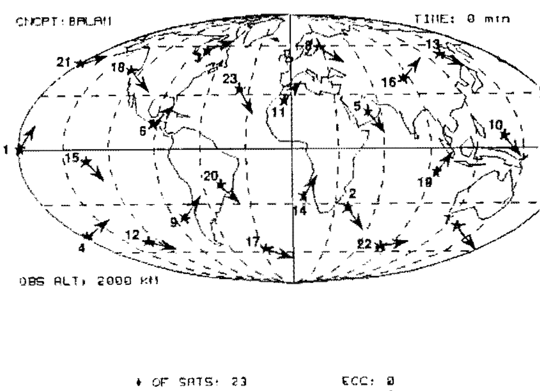


Figure 12. Instantaneous Coverage for 15 Satellite Constellation (Example I) at a Reduced Range of 4,500 km



PLANE	SAT #	NODE	ANOM
1	1	0	0
2	2	16	219
3	3	31	78
4	4	47	297
5	5	63	157
6	6	78	16
7	7	94	235
8	8	110	94
9	9	125	313
10	10	141	172
11	11	157	31
12	12	172	250
13	13	188	110
14	14	203	329
15	15	219	188
16	16	235	47
17	17	250	266
18	18	266	125
19	19	282	344
20	20	297	203
21	21	313	63
22	22	329	282
23	23	344	141

Figure 13. SPACE EGGS-Developed Instantaneous Positions For Example II

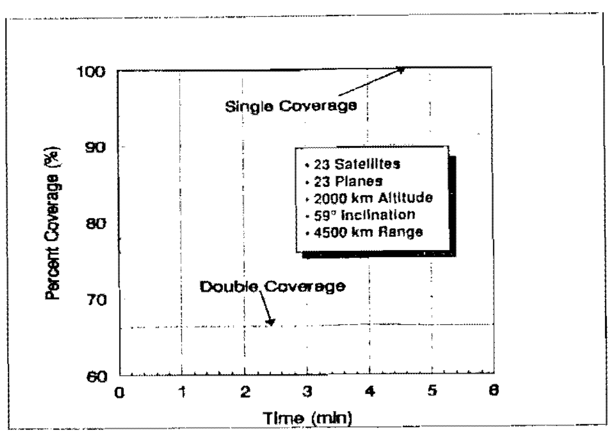


Figure 14. Coverage Over Time

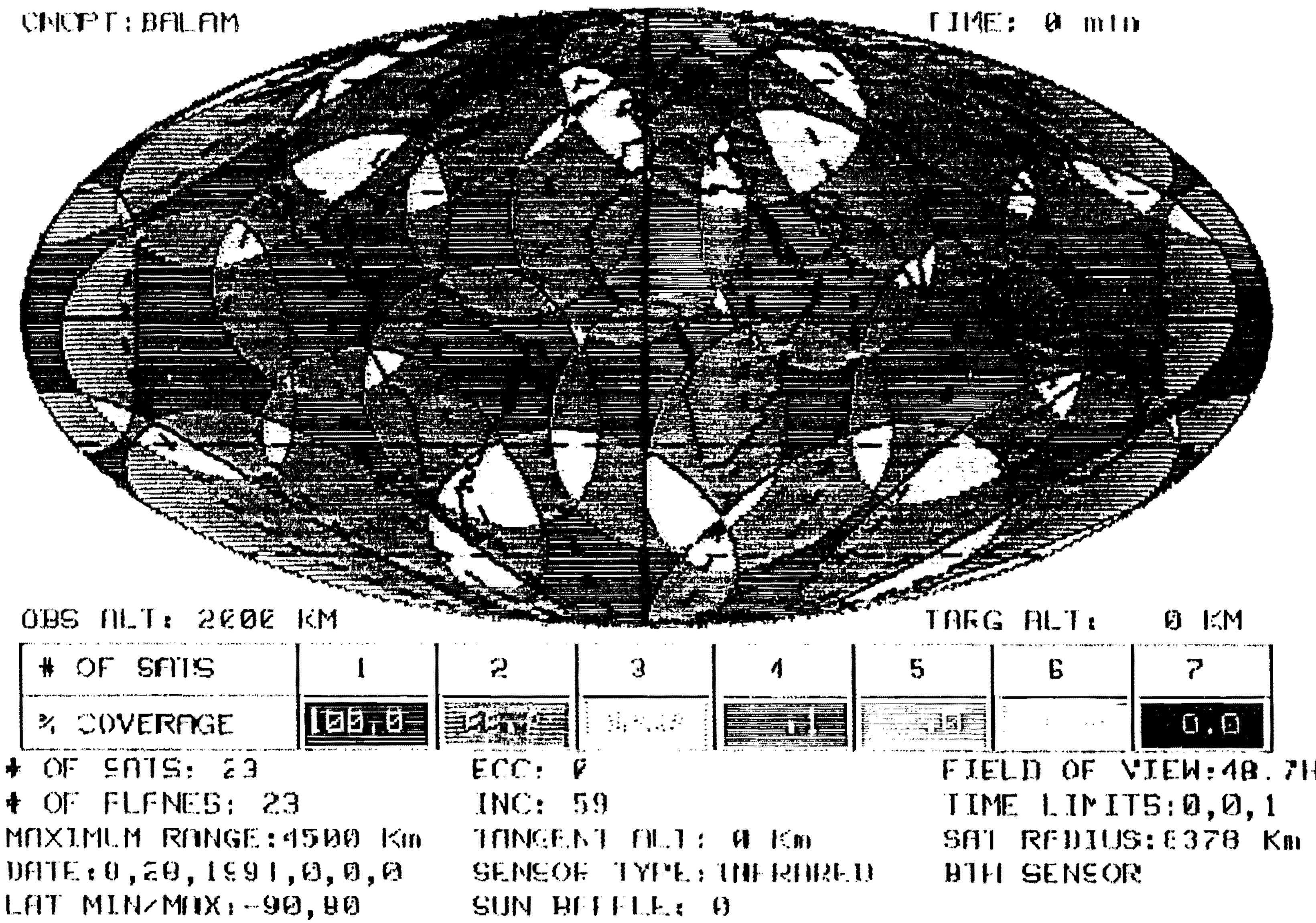


Figure 15. Instantaneous Coverage for 23 Satellite Constellation (Example II)

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