23 Space Logistics and Manufacturing

23.1 LEO Communications Constellations

Historical Approaches

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As will be appreciated from Chaps. 8 to 10, satellites in LEO have relatively limited coverage footprints on the surface of the globe by comparison with their cousins higher altitude orbits. Bearing in mind this footprint limitation, a system designer wishing to achieve a reasonable level of communications performance is automatically driven towards a constellation involving multiple satellites. Traditionally, both satellites and their launch vehicles have been expensive, and this raises obvious questions about the financial wisdom of constructing multi-satellite communications constellations in LEO—would smaller numbers of satellites in higher orbits not represent a more logical investment? And yet the most prolific satellite series in history, the Russian Strela-1 system, is a communications constellation which over its lifetime saw the launch of some 350 or so relatively short-lived satellites. And in the 1990s, Iridium, Globalstar and Orbcomm all invested large sums in the creation of LEO communications systems.

The explanation behind the apparent contradiction relates to the user communities that these satellite systems were endeavoring to serve, and the locations of those users on the surface of the Earth. These user communities were either mobile, with small, low-power hand-held receivers, or, (in the case of the Strela-1 system), espionage agents who presumably had no desire to advertise their presence by erecting a satellite dish on the roof! In most cases, such terminals will not be "cooperative," (in the sense that the user will not necessarily be able to ensure a clear line of sight to the satellite, or use a highly directional antenna to track the satellite as it moves across the sky). In order to establish a satisfactory link budget to such an uncooperative terminal, it is necessary to ensure that the Effective Isotropic Radiated Power (EIRP) from the satellites is sufficient to overcome these limitations. Specifically, the system designer must make certain that the free space path loss, (which is dictated by the range between the transmitter and receiver), does not render the system infeasible.

The early Russian Strela-1 satellites were simple, mass produced devices. Approximately spherical, and lacking attitude control, they were equipped with relatively low gain, low frequency antennas, and were launched in batches of 8 into a 1,500 km altitude, high inclination orbit. Lacking a propulsion system, they were deployed at intervals of a few seconds from the Cosmos launch vehicle, thereby gaining slightly different initial orbital parameters which would cause them to drift around their orbit plane relative to one another over time. More than one plane of these satellites was supported, but the lack of a station keeping system meant that they were, for statistical reasons, unable to guarantee uninterrupted coverage. The system was, instead, used to support a store-and-forward communication system for Russian agents worldwide.

The Strela-1 constellation was eventually superseded by a more sophisticated system called Strela-2, (later marketed commercially under the name Gonets in the West). This constellation was composed of larger gravity-gradient stabilised satellites which could perform real-time communication, if both user and receiver were within the coverage footprint of the satellite, but could also relay data in a store and forward fashion if this were not the case. Since they were gravity stabilized, the satellites could exploit higher-gain, directional antennas, operating at higher frequencies than the Strela-1 system, and hence offering higher data rates. Like its predecessor, the Strela-2 system operated in high inclination orbits, also approaching an altitude of 1,500 km. The choice of orbital altitude may have been dictated in part by the desire to keep the satellites below the worst effects of the Van Allen radiation belts, although, (since all Russian satellites during this era were pressurized designs), their electronics would have received a degree of shielding from the pressure vessel in which they were housed.

However, the Van Allen radiation belts certainly represent a constraint on the orbital options open to the LEO communications system designer if a reasonable design lifetime is to be achieved. It is tempting to treat orbital altitude as a completely free parameter along with the other orbital parameters such as inclination and right ascension, but in practice, the radiation doses that a satellite receives from protons trapped in the Earth's electromagnetic field at altitudes above 1,500 km will have implications for the relative amount of shielding required by the satellites, or the effective lifetime of the hardware, or both.

Due to the availability of lower latitude launch sites, access to GEO was easier for Western nations than it was for Russia. As a result, there was a greater focus on high altitude communications, and significant investment in LEO communications constellations did not take place until the 1990s. The increasing popularity of mobile communications led a number of providers to envisage global, satellite-based systems that would service regions where cellular towers were unavailable.

Several concepts were proposed to meet this communications requirement, and three reached the stage of actually launching satellites, Iridium, Globalstar and Orbcomm. These networks took different approaches to their constellation design, and it is instructive to compare the different approaches that were adopted to both the space and ground segments.

Iridium selected a system design that placed significant complexity in the space segment. The satellites were equipped with inter-satellite links which allowed messages to be passed between the satellites in real time. The satellites in the operational Iridium constellation were originally configured in seven planes of 11 operational satellites, (and one spare per plane), giving a total of 77 operational vehicles, (and hence the origin of the name for the constellation, since iridium is the 77th element in the periodic table). These 77 satellites were originally illustrated in truly polar orbits at an altitude of 765 km. A subsequent revision to the Iridium constellation involved a move to a higher orbital altitude, 780 km, allowing each individual satellite to provide coverage of a larger region of the Earth's surface. This change allowed Iridium to reduce the number of orbital planes to 6, and the number of operational satellites to 66, (and at this point the 11 spare satellites were "counted" in order to preserve the rationale for name of the constellation; possibly because the 66th element in the periodic table, dysprosium, sounds more like a laxative than a satellite constellation!). The change to the number of planes was also accompanied by a change in the orbital inclination to 86.4 deg. This was done because the orbit coverage pattern of the Iridium constellation requires precise maintenance of the orbital altitude, and it was belatedly realised that truly polar orbits would result in the Iridium satellites repeatedly risking collisions as the vehicles in different planes passed directly over the poles.

The Iridium constellation design required careful phasing between planes in order to minimize the number of satellites required. As described in Sec. 10.6.2, the system relied on overlapping footprints between adjacent planes (a design sometimes described in the literature as the "streets of coverage" approach). The satellite footprints in adjacent planes intersect as illustrated in Fig. 10-28 (Sec. 10.6.2) to ensure that there are no gaps in the overall coverage pattern. Clearly this pattern can be maintained by satellites moving in the same direction in adjacent planes, but at the "seam" in the constellation between the ascending and descending passes, the satellites are moving in opposite directions, and the coverage footprints move past one another. As a consequence, the plane separation between planes 1 and 6 of the Iridium constellation is approximately 25 deg, whereas the separations between the remaining 5 planes is on the order of 31 deg.

There is a significant contrast between the Iridium constellation coverage and that provided by the the Orbcomm and Globalstar systems. The latter two constellations utilize lower inclination orbits, ensuring that the satellites spend more of their time over the populated regions of the globe (where the potential paying customers are!). Due to the increased proportion of the time for which the individual satellites can provide an effective service, both Globalstar and Orbcomm required fewer satellites in their system design. In the case of Globalstar, an orbit altitude of 1,410 km and an inclination of 52 deg permitted the use of 48 satellites, consisting of 8 orbit planes with six satellites in each. This constellation provides continuous coverage of latitudes 70N to 70S, which corresponds to 80% of the Earth's surface, but pretty close to 100% of the Earth's population. In the case of Orbcomm, the principal component of the constellation was 3 planes of 8 satellites at an inclination of 45 deg and an altitude of 780 km. This was to be augmented by further planes of satellites passing over the equator and over the poles, for a total of 36 satellites. Again the coverage of the constellation was not global, and in some areas, gaps in the constellation pattern at lower inclinations resulted in less that 100% system availability. It should be noted that neither the Orbcomm or Globalstar systems featured inter-satellite links, with the result that their investment in terrestrial gateway facilities had to be proportionately greater than that of Iridium in order to deliver real-time connectivity into the Public Switched Telephone Network (PSTN). Again the distribution of the Earth's continents represents a limiting factor, since there are inaccessible regions, (and especially over the oceans!) where it is not practicable to site a ground station, and so the satellites are required to operate in a store-and-forward communications mode during the times when they are out of sight of land.

It could be argued that Iridium's choice of constellation configuration was inappropriate, particularly in terms of the inclination that was chosen. In defence of the Iridium constellation, it is frequently suggested that there was a very good reason for the choice of orbit: that the US government was paying for a proportion of the Iridium system in order to provide a means of communicating with strategic submarine assets operating in Northern waters. Nevertheless, it is hard to escape the conclusion that Iridium could have saved themselves a significant proportion of their investment if only some of their orbit planes had been near-polar.

What appears to have been overlooked, to some degree, in the rush to deploy these LEO communications systems, is the geographic distribution of the potential user base. The Earth's continents are significantly biased to the Northern hemisphere, and so, consequently, is the Earth's population. A graph illustrating this is provided at Fig. 23web-1.

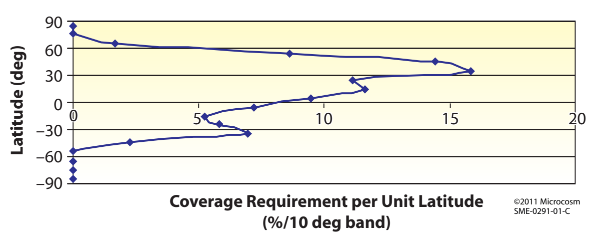

Fig. 23web-1. The Distribution of the World's Population Against Latitude.

One constellation proposal which clearly took this factor into account, (and which also exploited the fact that satellite orbits can be elliptical as well as circular), was the Ellipso concept.

Ellipso consisted of two different satellite components:

- The Borealis elliptical orbit element, which involved 10 satellites in two retrograde orbit planes at the critical inclination of 116.6 deg and with argument of perigee values close to 270 deg, (i.e. in the southern hemisphere), The apogee altitude of 7,605 km and perigee altitude of 633 km correspond to an orbit period of three hours, and the apogee position over the northern hemisphere optimizes its coverage of this region
- The Concordia component, which comprised seven circular orbit satellites operating in the equatorial plane at an altitude of 8,050 km. This equatorial component provides coverage over a band from 50 deg north to 50 deg south

The combined coverage pattern of the Borealis and Concordia components of the constellation is illustrated in Fig. 23web-2.

It can be seen that the coverage provided by the two components overlap over the mid-latitude bands in the northern hemisphere, which is where the peak of the population distribution occurs.

The fact that this coverage can be provided with just 17 satellites is clearly attractive, but a word of caution is appropriate here. Both components of the Ellipso constellation operate in orbits that would experience a significant radiation dose, (principally from energetic protons at these altitudes). While this is not necessarily fatal to the concept, to achieve a comparable system lifetime, appropriately hardened electronic components would need to be selected to withstand this level of radiation. A satellite designer would also need to think carefully about the choice of structural materials to enhance the physical protection that is provided to the internal circuitry. Clearly the net result of such shielding would be to make the satellites heavier, and, equally clearly, this would obviously incur additional launch costs.

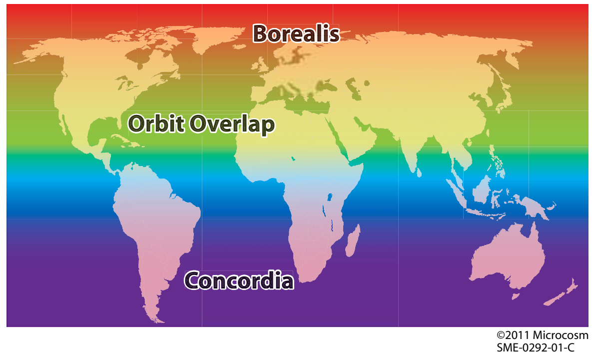

Fig. 23web-2. The Coverage Provided by the Ellipso Constellation.

It should also be noted that the retrograde orbit selected for the Borealis component is a more challenging proposition for the launch system as a result of the need to overcome some component of the Earth's rotation, (the degree to which this is necessary will be dictated by the latitude of the launch site). The reason for its selection is that it can be shown to meet the condition for sun-synchronizm outlined in Sec. 9.5.3. Though such orbits are typically selected for imaging missions, this regression of the line of nodes would potentially simplify the satellite platform design, permitting fixed solar panels to be used, and also providing a permanent "cold face" for the satellite radiators.