# Non-redundant HexSat formations for improved L-band data

Matas Gelžinis[1], Alexander Wittig[2]

[1] PhD candidate
[2] Associate Professor
Department of Aeronautics and Astronautics, University of Southampton,
University Road, Southampton, SO17 1BJ, Hampshire, UK - (mg2n18, a.wittig)@soton.ac.uk

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## 1. Introduction

Surface soil moisture and sea surface salinity are key variables in hydrology, linking the Earth's surface with the atmosphere. Observing these variables from space with a reasonable ground resolution is hindered by the long L-band wavelengths at which they are best sensed. As a result, antenna diameters required for sub-10 km resolution data become prohibitively large. The Soil Moisture and Ocean Salinity (SMOS) mission mitigated the need for a large antenna by employing aperture synthesis, combining measurements from 69 small antennas. Distributed in a Y-shaped grid on three deployable arms this structure achieved a synthesised aperture the size of the whole sparse grid (Kerr et al., 2001). However, even before the launch of SMOS it was recognised that the 40 km spatial resolution could be improved by flying multiple satellites in a close formation. To achieve it, works of (Goutoule and De Boer, 2000) and (Martín-Neira et al., 2023) both propose a formation of three wide satellites. In this work, we show how a larger number of smaller satellites can be arranged to improve the interferometric array's point response in terms of the half-power beamwidth and maximum sidelobe levels.

## 2. Array shapes

One key measure in synthetic aperture arrays is how well they cover the normalised relative spacing (UV) space. By correlating the signals of every pair of antennas, it is possible to sample the visibility function and recover desired data. It is important to sample many UV points to make this recovery as accurate as possible. However, if every UV point is only sampled once (non-redundant), then any antenna failures will introduce holes in UV space, increasing noise. Work in (Zurita et al., 2013) found that to balance coverage area with UV point redundancy antennas should be arranged in a hexagonal shape, which was then adopted in (Martín-Neira et al., 2023).

Hexagons also benefit from tiling well in UV space, when multiple hexagonal antenna arrays are arranged the right distance apart. The question of how these hexagons should be placed in space is analogous to the antenna placement problem; it is a trade-off between redundancy and UV coverage. However, since UV point redundancy is ensured by the hexagonal arrangement of antennas on each satellite, the satellites can be flown in non-redundant formations, where every inter-satellite spacing is unique, to increase UV coverage.

The work in (Golay, 1971) presents compact 2D point arrays with non-redundant relative spacings for up to 12 points and threefold symmetry. These arrays are referred to as Golay arrays, with a number to indicate the number of points, and a subscript to clarify if that array is from the first or second sequence of the original paper. When scaled appropriately these point arrays can serve as the center positions for satellites in formations. For example, Fig.1 shows a Golay6 formation of 1.4 m wide satellites and Fig.2 presents the resulting UV coverage. The colour of each UV point shows its redundancy. It can be seen that the vast majority is doubly redundant (light blue), with only the very corner points being irreplaceable, and only the centre UV tile having an unnecessarily high redundancy.

## 3. Formation performance

In Tab.1 we show the synthetic beam's maximum sidelobe levels and 3 dB beamwidth for hexagons in different Golay formations. Hamming apodization window is used and the smallest antenna spacing is kept at the alias-free condition, ensuring UV point density is the same in every case and keeping results comparable with (Martín-Neira et al., 2023). While the number of satellites in a formation increases, individual satellite size is reduced and the total number of antennas is kept the same.

Lower sidelobe levels and smaller angular resolutions for formations with more satellites are attributed to fewer points having high (4+) redundancy. Instead, these points end up as unique baselines, contributing to performance. 216 antennas arranged across six satellites will have 11% more unique baselines than if placed across three larger spacecraft. Other Golay formations in Tab.1 have even more unique baselines but offset the benefits by introducing holes in UV space.

Furthermore, flying a larger number of smaller satellites has a key benefit of satellite redundancy. A malfunctioning satellite in a formation of three would remove more than half of the total UV coverage, with the remainder being arranged along a single spatial direction. An equivalent individual malfunction in a formation of six would remove less than a third of the total UV coverage and introduce holes in UV. However, these can be removed by reorganising the formation for the new number of satellites.

## 4. HexSats

One interesting development in nano-satellite technology are HexSats, a proposed flat, around 2.5 cm thick and roughly 1 m in diameter, satellite platform well suited for high power and large aperture applications (Saddul et al., 2024). Their structure weighs around 3 kg and can provide more than 200 W of power to the payload. In addition to low drag, the thin form of a HexSat allows them to stack well and the hexagonal shape

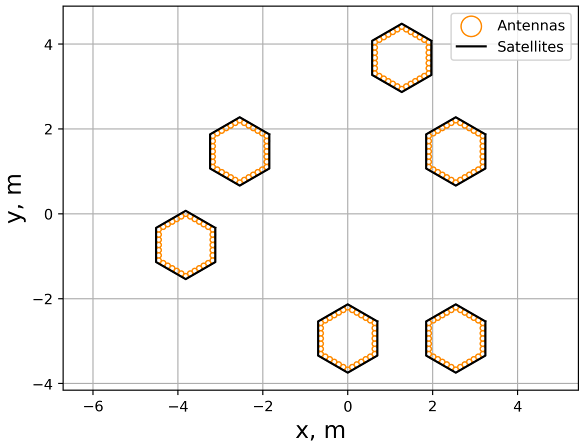


Figure 1. Six hexagonal 1.4 m wide satellites arranged in a Golay6 formation. The total number of antennas is 216, the same as in (Martín-Neira et al., 2023).

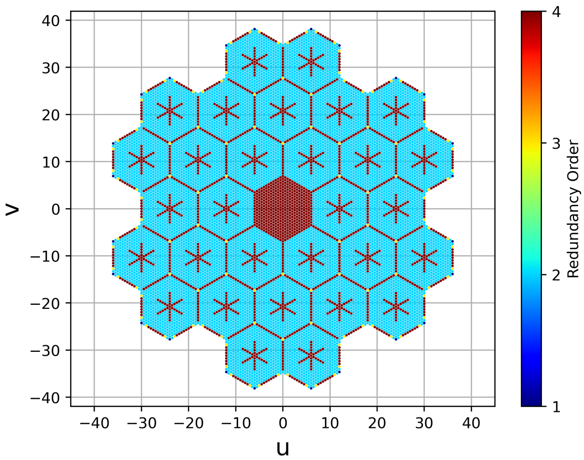


Figure 2. UV coverage and redundancy order for antenna arrangement from Fig.1. Virtually every baseline is at least doubly redundant (light blue colour) due to the hexagonal arrangement of antennas on each individual satellite.

| D (m) | No. Sat. | Type | Max sidelobe(dB) | BW |
|---|---|---|---|---|
| 3 | 3 | Golay3 | -14 | 1.5° |
| 1.4 | 6 | Golay6 | -14.82 | 1.47° |
| 0.9 | 9 | $Golay9_1$ | -14.45 | 1.36° |
| 0.6 | 12 | $Golay12_2$ | -12.48 | 1.23° |

Table 1. Golay formation performance with a total of 216 antennas each. D is the individual hexagon diameter and BW is the 3 dB (half-power) beamwidth. Data in the first row is from (Martín-Neira et al., 2023)

gives a superior packing efficiency in a circular rocket fairing when launching more than three stacks of satellites.

HexSats are proposed to use many small thrusters that fit the thin form factor for orbit and formation keeping. These small thrusters produce thrust in micro-Newton levels and are distributed along the facesheets and the thickness of the satellite. In practice, this distributed micro-propulsion system (D$\mu$PS) would use Vacuum Arc or Electrospray Thrusters to provide full 3-axis control, and is shown in Fig.3.

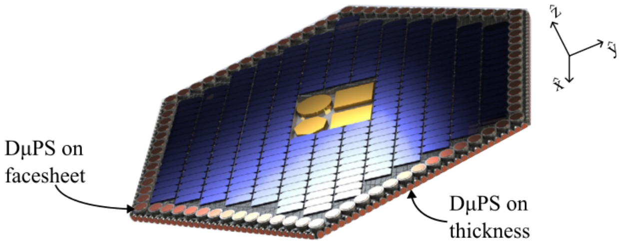


Figure 3. "HexSat concept: A flat hexagonal satellite using the D$\mu$PS for orbital and attitude actuation" (Saddul et al., 2024)

As evident from Tab.1, nine HexSats could achieve 1.36° angular resolution, which can translate to a 10 km nadir spatial resolution from an altitude of around 420 km. Since HexSats are well suited to even lower altitudes, the nadir spatial resolution can be reduced to less than 6 km at an altitude of 250 km.

HexSats have the potential to improve soil surface moisture and sea surface salinity data, however, several challenges remain. The thin form factor is a major restriction, and it is not yet clear how all components and subsystems required for interferometric measurements will fit. Communicating, transferring data, and correlating signals from multiple satellites presents further challenges that need to be addressed. Finally, as in any close satellite formation, plume impingement and material deposition on nearby spacecraft can be problematic. Further research to solve these issues is ongoing.

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