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## **NetSat-4G**

# **A four nano-satellite formation for global geomagnetic gradiometry**

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**Abstract:** This paper proposes a concept for a Global GeomaGnetic Gradiometry (4G) nano-satellite mission. The proposed concept makes use of a formation of four nano-satellites carrying vector magnetometers and flying in a Cartwheel-Helix formation at low altitude. The use of four satellites makes possible the simultaneous measurement of the geomagnetic gradients in all three directions (east-west, north-south and radial), and thus the realisation of a full gradiometry mission. The concept foresees the use of a miniaturised propulsion system for formation acquisition and maintenance, allowing not only to setup optimal formation geometries for optimal gradient retrieval but also to extend the mission lifetime at the targeted low altitude. The preliminary results of an end-to-end simulation are presented, and the gradient concept for NetSat-4G demonstrated. Given the constraints inherent to a nano-satellite platform, measurement performance is still, as expected, inferior to what can nowadays be achieved with larger and more expensive missions. Despite the disadvantages, the proposed concept is still considered pertinent as it would allow, for the first time, to implement a full geomagnetic gradiometry mission.

**Keywords:** mission concept, magnetic gradiometry, NetSat, nano-satellites, formation flying

## **1. MISSION SCIENCE OBJECTIVES**

The Networked Pico-Satellite Distributed System Control (NetSat) mission, under development at the Zentrum für Telematik (ZfT), has as primary objective the in-orbit demonstration of autonomous formation control of four pico/nano-satellites [1]. At the same time, such a four nano-satellite formation opens the door to explore new and different types of science. This mission concept investigates the use of NetSat for retrieval of the full geomagnetic gradient tensor.

Retrieval of the full gradient tensor from multi-point satellite measurements has shown to improve determination of the small-scale lithospheric magnetic field and the high-degree secular variation [2] [3], when compared to having only measurements of the field components. ESA’s Swarm mission provides already, with its lower pair of satellites, estimation of the east-west gradients with high accuracy, allowing retrieval of north-south oriented crustal structures. Gradients in the other directions are, however, not possible with the current constellation. Previously, NASA’s ST-5 mission, consisting of three micro-satellites flying in a string-of-pearls constellation, had already shown the potential of using magnetic field gradients for the study of the lithospheric field [4]. At the nano-satellite scales, the use of constellations for the study of the Earth’s magnetic field has been previously suggested [5]. The proposed formation of four nano-satellites would make possible the implementation of a full gradiometry mission, providing simultaneous determination of gradients in all three directions. Such an approach has been proposed as a possible future way of exploring Earth’s magnetic field [6].

## 2. SCIENCE ORBIT

### 2.1. Orbit and Formation Selection

The formation targets a near-polar orbit with a mean altitude of 400 km. Three satellites are placed in nearly the same orbital plane in a Cartwheel type of configuration with the same eccentricity, and with the arguments of perigee separated by 120 deg. A fourth satellite is placed in a different plane with the same inclination but with an offset in right ascension of the ascending node (RAAN) and a smaller eccentricity.

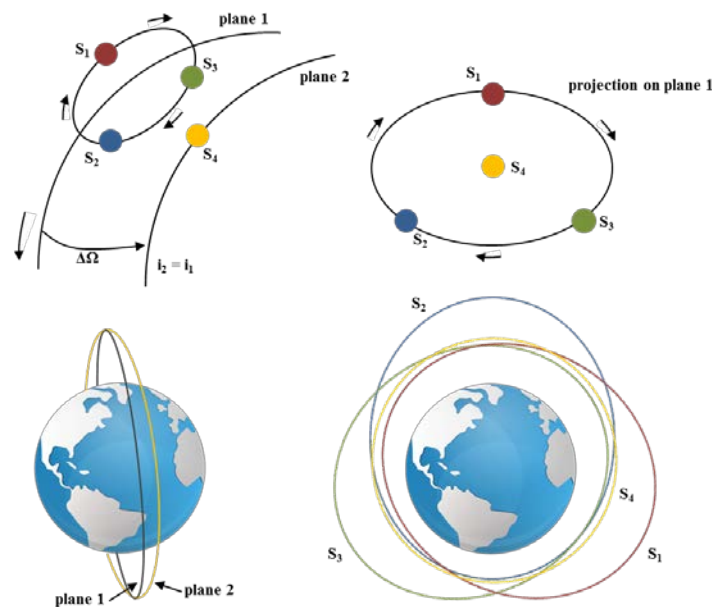


Figure 1: target NetSat Cartwheel-Helix configuration with four satellites (not to scale)

By adjusting the eccentricity of  $S_1$ ,  $S_2$  and  $S_3$ , and thus the size of the ellipse, the inter-satellite distance corresponding to the north-south and radial gradients can be modified. Similarly, by changing the offset in RAAN between the two planes, the inter-satellite

distance corresponding to the east-west gradients can be equally adjusted. For this first analysis the following orbits are selected:

	$S_1$	$S_2$	$S_3$	$S_4$
$a$ [km]	6778	6778	6778	6778
$e$ [-]	0.0057	0.0057	0.0057	0.0001
$i$ [deg]	87.4	87.4	87.4	87.4
$\Omega$ [deg]	$\Omega_1$	$\Omega_1 + 0.2$	$\Omega_1 + 0.1$	$\Omega_1 + 1.4$
$\omega$ [deg]	45	$\omega_1 + 120$	$\omega_1 + 240$	$\omega_1 - 90$
$M$ [deg]	$360 - \omega_1$	$M_1 + 240$	$M_1 + 120$	$360 - \omega_4$

**Table 1: target NetSat science orbits (osculating orbital elements)**

Like for ESA's Swarm satellite mission, an inclination of around 87.4 deg and a separation of 1.4 deg in RAAN between the two planes is chosen. The eccentricity of  $S_1$ ,  $S_2$  and  $S_3$  is selected such that the minor and major axis of the ellipse measure approximately 77 km and 155 km, respectively. Even though the inter-satellite distances are large enough so that differential atmospheric drag does not introduce risks of collision, a small additional offset in RAAN can be added between  $S_1$ ,  $S_2$  and  $S_3$  to introduce a separation in the relative inclination vector, and thus guarantee a safe relative e/i-vector separation. No particular constraint is imposed on the formation local time of ascending node.

To minimise the effect of orbit perturbations in the relative motion, in particular of Earth's  $J_2$  term, the reference orbits in table 1 are redefined in terms of Brouwer mean orbital elements. For an arbitrarily chosen RAAN  $\Omega_1 = 0$  deg this holds:

	$S_1$	$S_2$	$S_3$	$S_4$
$a$ [km]	6768.190	6768.190	6768.190	6768.190
$e$ [-]	0.00453319	0.00453319	0.00453319	0.0001
$i$ [deg]	87.398126	87.398126	87.398126	87.398126
$\Omega$ [deg]	359.999956	0.200048	0.100025	1.400010
$\omega$ [deg]	38.599941	177.441005	278.384583	252.210099
$M$ [deg]	321.399884	182.559785	81.6146359	107.789829

**Table 2: target NetSat science orbits (Brouwer mean orbital elements)**

## 2.2. Formation Acquisition and Control

Using a standard CubeSat deployer in a piggyback launch, the four nano-satellites are injected in nearly the same orbit. Assuming a direct injection at the target altitude and inclination\*, the following series of manoeuvres are required to setup the target formation, as defined in table 2:

- 1) Reduce the mean eccentricity of  $S_1$ ,  $S_2$ ,  $S_3$  and  $S_4$  to the target value;
- 2) Introduce the target mean RAAN separation between  $S_1$ ,  $S_2$ ,  $S_3$  and  $S_4$ . This is achieved by temporarily changing the inclination of  $S_2$ ,  $S_3$  and  $S_4$  by a small amount such as to initiate a relative drift in RAAN. Once the required separation in RAAN is achieved the inclination is changed back to its initial value to stop the drift;
- 3) Introduce a 120 deg offset in mean argument of perigee between  $S_1$ ,  $S_2$  and  $S_3$ , and a -90 deg offset between  $S_1$  and  $S_4$ ;

\* The only requirement on the orbit inclination and altitude is that it shall be near-polar with a mean altitude between 400km and 500km.

- 4) Perform orbit phasing manoeuvres as required to adjust the mean anomaly of  $S_1$ ,  $S_2$ ,  $S_3$  and  $S_4$ .

Note that in practice the manoeuvres for steps 1, 3 and 4 are, as much as possible, combined and jointly optimised. Throughout the mission, manoeuvres are required to control the relative eccentricity vectors magnitude and angle and to correct differential drag effects such as to maintain the formation geometry. No manoeuvres are foreseen to control the relative inclination vector.

Table 3 below summarises the estimated  $\Delta V$  requirements for formation acquisition and maintenance assuming an injection eccentricity of 0.0073.

	Acquisition [m/s]	Maintenance [m/s] (1 year)
$S_1$	< 54	< 39
$S_2$	< 58	< 39
$S_3$	< 56	< 39
$S_4$	< 68	< 24

**Table 3: estimated required  $\Delta V$**

Once the fuel is exhausted the formation is left to drift freely. From then on, and even though the initial geometry can no longer be maintained, the mission would still produce useful gradient measurements in particular in the north-south direction. Assuming a launch in 2018, and using solar cycle 23 for the full propagation as recommended by ECSS [7], re-entry is expected to occur within 4 years after fuel exhaustion.

### 3. CONCEPTUAL SYSTEM DESIGN

The current spacecraft platform design concept makes use of a standard 3U nano-satellite structure with deployable solar arrays and maximises use of commercial off-the-shelf (COTS) components. This includes miniaturised star-trackers with < 10 arc-sec cross-axis accuracy, a software-defined radio (SDR) GNSS receiver with better than 5 m position determination accuracy, and a cold-gas micro-propulsion system for orbit acquisition and maintenance. The low-rate inter-satellite link, in place to enable the primary mission objectives, could also be used for better inter-satellite clock synchronisation. For the instrument, the current approach foresees the use of vector magnetometers with better than 4 nT accuracy and placed at end of a deployable boom for higher magnetic cleanliness.

#### 3.1. Sensitivity Analysis

The final errors in the magnetic field gradients are dominated by uncertainties in:

- Attitude determination;
- Instrument measurements due to inherent sensor inaccuracy, sensor miscalibration, or unaccounted electromagnetic interferences from the satellite platform;
- Position determination.

A first analysis was performed to estimate the sensitivity of the measurements to these three error sources using a dipole model of the Earth’s magnetic field. For vector measurements the overall error is, as expected, largely dominated by uncertainties in attitude determination and instrument measurement errors. For a 10 arc-sec attitude determination accuracy, the average errors over one orbit are between 6 and 12 pT/km for the north-south gradients. For a 4 nT instrument measurement accuracy, the average error over one orbit is around 22 pT/km for the north-south gradients. Improving the instrument accuracy to 1 nT would reduce the error to 6 pT/km. For scalar measurements the overall error is dominated by instrument measurement errors, while uncertainties in position determination contribute only marginally to the error budget. A 5 m position determination uncertainty leads to errors below 0.08 pT/km for the north-south gradients.

### 3.2. Attitude Determination

The concept foresees the use of at least two star trackers to guarantee maximum attitude determination accuracy in all three directions. Table 4 below gives an overview of available star-trackers for nano-satellite platforms.

	Cross-Boresight [arc-sec]	Boresight [arc-sec]	Notes	Ref.
<i>ST-16</i>	< 7	< 70	In-flight testing	[8]
<i>BCT Nano</i>	7	24	Ground testing	[9]
<i>ST-200</i>	30	400	Ground testing	[10]

Table 4: COTS star-trackers

Performance has still to increase by one order of magnitude to reach Swarm-like accuracies at less than 1 arc-sec.

### 3.3. Orbit Control

Orbit control, required for formation acquisition and maintenance, is performed using a cold/warm-gas micro-propulsion system. The total delivered  $\Delta V$  for a 6 kg nano-satellite for two of the evaluated options is summarised in table 5 below.

	Propellant Mass [g]	Volume	$\Delta V$ [m/s]	Ref.
<i>PUC-184-SO2</i>	863	1U	106	[11]
<i>CHIPS-R134a</i>	700	1U	85	[11]

Table 5: COTS micro-propulsion systems

Both of the evaluated micro-propulsion systems would allow to setup the initial orbits and run the mission in the target formation for at least eight to ten months within the nano-satellite mass, volume and power constraints.

### 3.4. Vector and Scalar Magnetometers

Table 6 presents two examples of flight-proven miniaturised magnetometers being considered in the NetSat-4G context. DICE is in orbit since 2011 and CINEMA since 2012.

	Type	Rated Accuracy [nT]	Ref.
<i>CINEMA MAGIC</i>	AMR	< 2	[12]
<i>DICE SciMag</i>	AMR	5	[13]

Table 6: magnetometers overview

#### 4. END-TO-END SIMULATIONS

A simulation of a full gradiometry mission is performed using synthetic data of the magnetic field vector from the CHAOS-5 model based on the orbits defined in table 2. One error free dataset and one dataset with added attitude and position determination errors (10 arc-sec and 50 m,  $3\sigma$ ) are generated for a period of one month. Subsequently, three models, NSVM, NSGM and NSGM\_D, are determined from:

1. Error free vector measurements only (NSVM);
2. Gradients derived from error free vector measurements (NSGM);
3. Gradients derived from vector measurements with added attitude and position determination errors (NSGM\_D).

The resulting models are then compared with the original CHAOS-5 input model. Figure 2 and figure 3 below summarise the preliminary results.

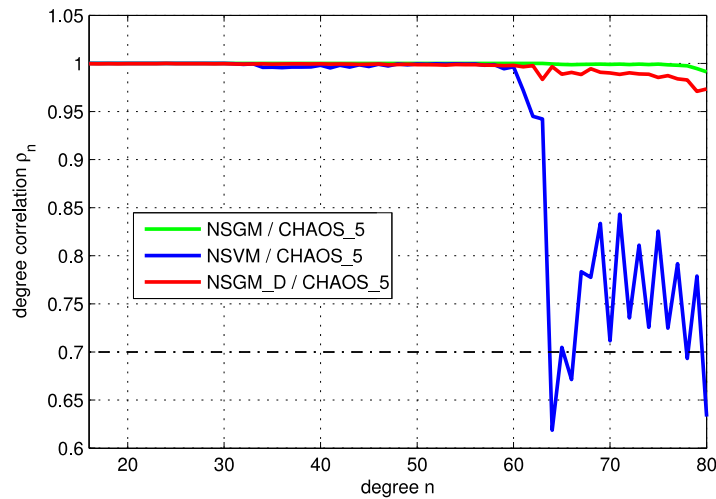
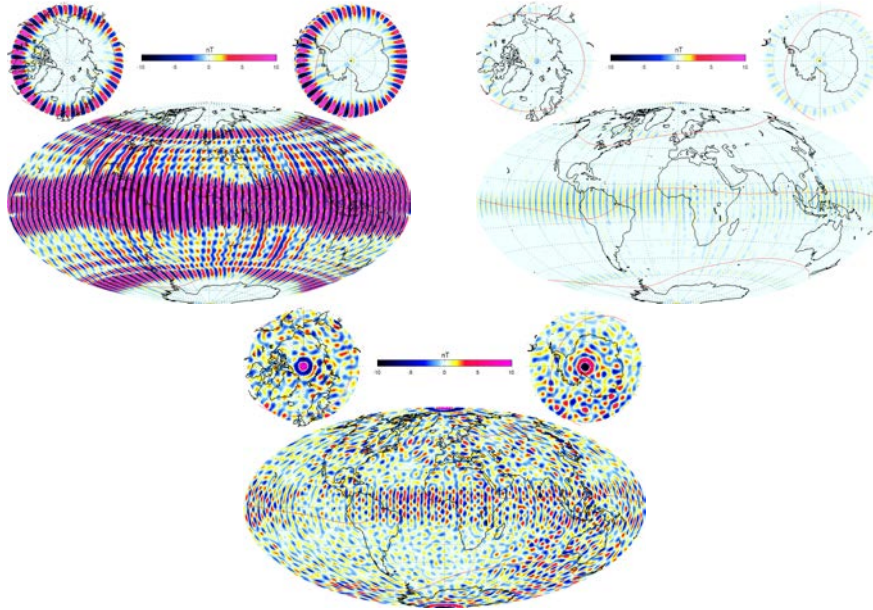


Figure 2: correlation to the CHAOS-5 model for field estimation based on: a) NSVM – error free vector measurements (blue), b) NSGM – error free gradient measurements (green), c) NSGM\_D – gradients derived from vector measurements with 10 arc-sec ( $3\sigma$ ) attitude determination error and 50 m ( $3\sigma$ ) position determination error (red)



**Figure 3: lithospheric field radial component differences with respect to CHAOS-5 model: a) NSVM – error free vector measurements (left), b) NSGM – error free gradient measurements (right), c) NSGM\_D – gradients derived from vector measurements with 10 arc-sec ( $3\sigma$ ) attitude determination error and 50 m ( $3\sigma$ ) position determination error (bottom)**

Figure 2 shows the correlation between the original CHAOS-5 model and the three derived models. It is shown that using gradients, and despite the short dataset (one month), coefficients up to degree 80 can be obtained with relatively good agreement to the CHAOS-5 model. Furthermore, when attitude and positioning errors are introduced, the model derived from gradients is still better than the one derived from error free vector measurements only. The same behaviour is displayed in figure 3, now depicted in terms of the differences in the lithospheric field radial component between CHAOS-5 and the derived models.

## 5. CONCLUSIONS

The continuous push for miniaturisation, in particular in the area of precise orbit and attitude determination, micro-propulsion systems and magnetic sensors, is making possible the realisation of full gradiometry missions using nano-satellites with mass below 6 kg.

The preliminary results of the end-to-end simulations demonstrate the gradient concept for NetSat. Further analyses with refined error budgets still need to be conducted to confirm the validity of these first results.

Despite the technical challenges for increased performance, the proposed concept is still considered pertinent as it would allow, for the first time, to implement a full geomagnetic gradiometry mission.

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