# NANO SATELLITE BEACONS FOR SPACE WEATHER MONITORING

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## ABSTRACT

This ESA-funded study, which started in November 2004, is investigating how current and emerging concepts for nanosats may be used to monitor space weather conditions and provide improved access to data needed for space weather services. The study has reviewed present and future micro and nano-technology developments that could be used to implement space weather monitoring by nanosats. It has also has established a set of space weather measurement requirements appropriate to nanosats solutions and developed a set of instrument and spacecraft solutions to address those requirements. These are now subject of system and mission analysis to derive costs for programme development, operation and maintenance over a ten-year period. As a last step the study will review the results of the previous stages and develop a report on the prospects for a space weather nanosat programme and recommendations on the measures needed to enable implementation of such a programme. To support this step a small workshop was held at ESTEC following the MNT Round Table.

## STUDY OVERVIEW

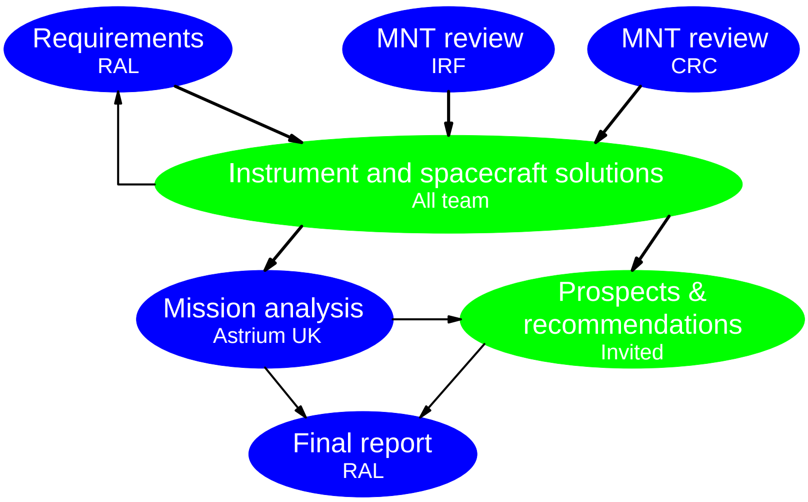


Fig. 1. Logical flow of the space weather nanosat study

The logic of the study is shown in Fig. 1. The study started with a preparatory phase comprising workpackages (a) to establish requirements for space weather monitoring by nanosats, (b) two reviews of micro- and nano-technology (MNT) status – one by Swedish Institute of Space Physics (IRF) drawing heavily on their experience with nanosats such Munin [1] and the other by EADS Deutschland (CRC) looking at the state-of-the-art on MNT devices and packaging – and especially at looking at prospects for devices based on Micro-Electro-Mechanical Systems (MEMS).

The outputs of the preparatory phase were fed into an intensive co-location meeting attended by all team members, and by ESA, at which ideas for spacecraft and instrument solutions were developed. These solutions were consolidated following the co-location meeting. In practice the consolidation of the instrument solutions raised ideas that provoked refinement of the requirements, e.g. where instrument concepts could be simplified to fit on a nanosat but would only address part of an existing requirement. This kind of feedback loop violates naïve ideas about the relationship between requirements and design, i.e. the waterfall model for system development, but is well-recognised as a normal and realistic technical approach.

At the time of writing the spacecraft and instrument solutions are subject of detailed mission analysis to assess how these solutions may be implemented. The final phase of the study will review and consolidate the previous study elements and also look at the prospects for using nanosats in space weather monitoring and to provide recommendations on actions that could turn those prospects into realities.

This report focuses on the work done so far – in particular the preparatory work (MNT status and requirements analysis) plus the instrument solutions.

**MNT STATUS**

**Nanosat experience**

IRF has actual flight experience with a nanosat that made space weather measurements. This was Munin [1] a 6 kg spacecraft with dimensions 21 x 21 x 22 cm as shown in Fig 2. The match box in right foreground shows the scale.

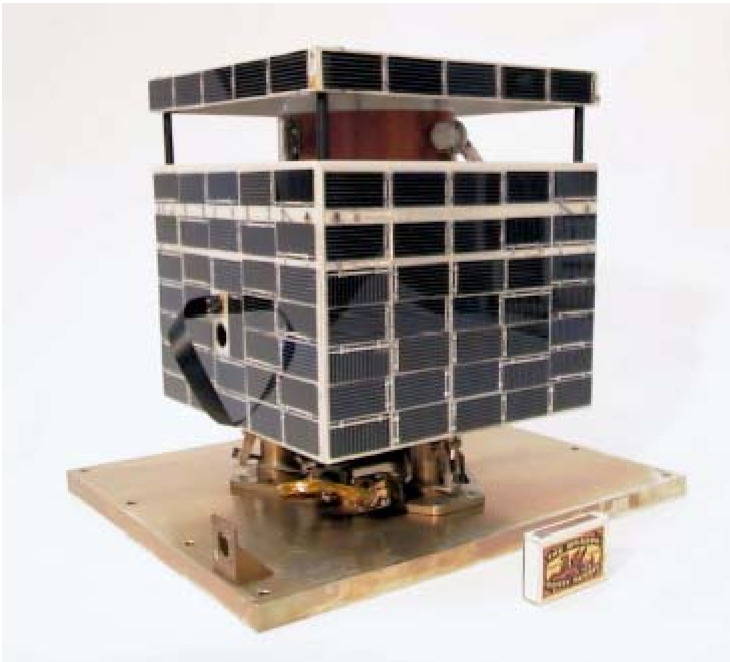

Fig. 2. Munin nanosat in flight configuration with the TM antenna folded/bent on left.

Munin was launched into a polar orbit (700 x 1800 km) in November 2000 and operated for 2.5 months before an on-board problem prevented uplink of commands. Munin was an experiment to build a nanosat using existing technologies; it carried instruments to observe space weather effects such as energetic particles and the aurora. These are shown in Table 1 below.

Table 1. Munin instrument characteristics

| | Meas. range | Field of view | Time res. (s) | Look dir. | Mass (g) | Power (mW) |
|---|---|---|---|---|---|---|
| MEDUSA, ions and electrons | 2 eV - 15 keV | 10° x 360° | 0.25 | 0°-180° | 588 | 1000 |
| DINA, ions and neutrals | 20 - 2400 keV | 5° x 30°, | 0.25 | 0°& 90° | 900 | 500 |
| HiSCC, visible imager | 320 x 249 pixels | 50° | 30-60 | 0° | 100 | 300 |

The spacecraft was powered by solar cells with 6W output and carried 4200 mAh capacity battery. The power consumption was 3 W nominal, rising to a peak of 9 W when transmitting to the ground station. The latter was based at Kiruna in Sweden and thus only used for the small parts of orbits when the spacecraft was visible. The radio link used frequencies in the UHF band at 400 to 450 MHz, thus allowing use of simple antennae on the spacecraft and the ground – and adaptation of an off-shelf transceiver (200g, 6W) for use on the spacecraft. This supported data rates up to 22 kbps.

The spacecraft was stabilised by inclusion of a permanent magnet which maintained orientation with respect to the geomagnetic field. This approach proved very successful and was entirely acceptable given the payload shown above. It would not, of course, be acceptable for a mission to make sensitive magnetic measurements. This would require a magnetically clean spacecraft or at least one whose fields were well-characterised.

Munin successfully made energetic particle measurements over its 2.5 month lifetime and returned much useful data to the ground. It showed that a simple space weather nanosat can be built today using existing technologies and the adoption of simple strategies (e.g. UHF radio link). But a long lifetime should not be expected due to limited availability of radiation-hardened components. One way to reduce the impact of radiation exposure, and a key lesson leaned from Munin, is the value of on-board autonomy. It would be very useful to eliminate the need for uplink of commands for routine operations. It was the failure of this aspect which brought Munin operations to a premature end.

**MNT state-of-the-art**

A wide range of MNT devices are now being developed by industry for use in future military and civilian technologies. Many of these may be adapted for use in space though it should be recognised that the key drivers for development of the basic MNT technology are often mass market applications such as cars and mobile phones. Key areas in which MNT devices may be useful for space weather nanosats include:

1. RF devices including resonators, switches, phase shifters and antennae. An area of particular interest is the development of MEMS-based phased-array antennae. In the long-term these could prove important because of the critical need for real-time data downlink to support space weather applications. A phased-array antenna could allow a nanosat to have a steerable downlink- thus improving the link budget available for a given power without the risks implicit when flying in a mechanically steered system in space.

2. Attitude and orbit determination and control. MNT developments relevant to this area include both detectors to monitor spacecraft dynamics and devices to control those dynamics. The detectors include optical detectors (e.g. MNT star mappers), magnetometers (to determine attitude with respect to the geomagnetic field) and MEMS-based sensors to determine the rate of angular motion. Control devices include MEMS-based momentum wheels and propulsion systems.

3. Power systems. Power is expected to be a critical issue for space weather nanosats because the area of solar cells will be limited by the small spacecraft dimensions and the need for sensor apertures looking out into space. Thus MNT-based developments in power generation could be important. These developments include development of new solar cell technologies with higher efficiencies as well as more novel systems such as thermo-generators, micro combustors, nuclear batteries and fuel cells.

Thus MNT devices have great potential to support development of space weather nanosats. But the successful inclusion of these devices on spacecraft will require development of robust techniques for high-density integration, e.g. using standardised interfaces and 3D-stacking technologies to allow integration of sub-components to build "systems in a package" (SIP). See Fig. 3 for an example. Several different types of material are now in use or planned for use in packaging of MNT devices. These include ceramics (such as alumina, $Al_2O_3$, and low temperature co-fired ceramics, LTCC), polymers (such as Kapton$^{TM}$ and Liquid Crystalline Polymer) and carbon nano-tubes.

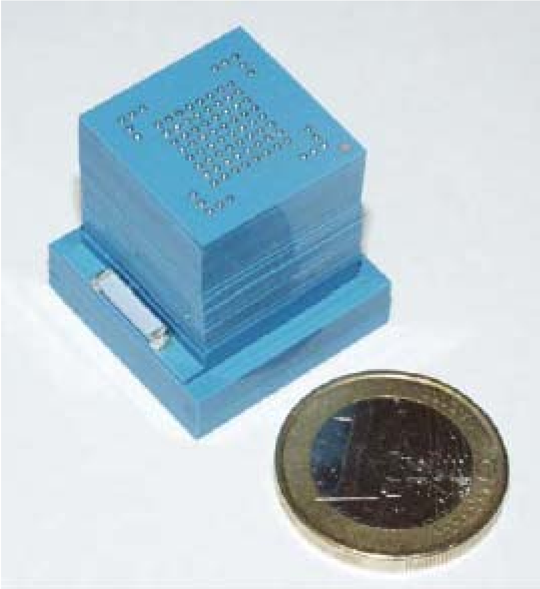

Fig. 3. An example of MNT packaging. An EADS micropack containing atmospheric and inertial sensors, power supply, data handling unit and RF transceiver. A 1 Euro coin is shown for size comparison.

The critical issues facing the application of MNT on a spacecraft are (a) system design and integration, where the small size presents a challenge for thermal management and electromagnetic compatibility, (b) packaging as already discussed and (c) the development of efficient procedures to qualify and validate these new technologies.

## REQUIREMENT ANALYSIS

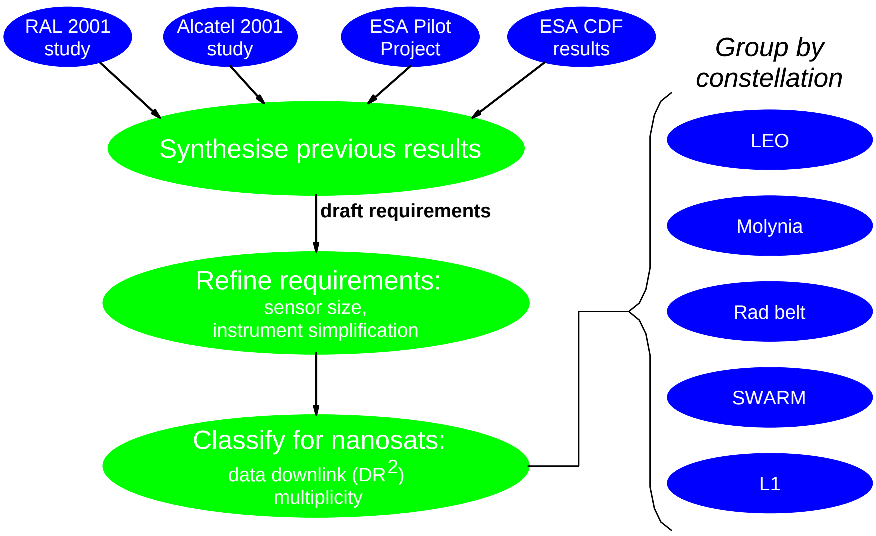


Fig. 4. Logic of the requirements analysis

The logic of the requirements analysis is shown in Fig. 4 above. The study did not have to perform a detailed collection of requirements as extensive work had already been done in previous ESA-funded studies, namely the two space weather programme assessments performed in 2000/2001 by teams led by RAL [2] and by Alcatel [3]. Thus the main task here was to merge the requirements developed in these studies. This was a major task because of the different methodologies used by the two teams. The RAL study produced a set of 74 consolidated system measurement requirements (CSMRs) of which 54 were space-based [4]. The Alcatel study listed 22 key parameters to be measured in space and provided a description of some 25 possible instrument solutions, which gave further insight into the underlying measurement requirements, e.g. time resolution [5]. A preliminary analysis of the two studies identified 110 combinations of CSMRs, key parameters and instruments that were candidates for detailed assessment. That detailed assessment then allowed us to extract some 34 unique requirements.

To verify the completeness of these requirements we compared them with the requirements used in the ESA CDF space weather study [6], which was carried out in parallel with the RAL and Alcatel studies, and with the requirements emerging from the present Space Weather Applications Pilot Programme [7]. The CDF study did not yield any new requirements, which is to be expected as its requirements were drawn from the RAL and Alcatel studies. However, the analysis of the Pilot Programme did expose one new requirement – namely the need for monitoring of the solar farside to provide 14-day-ahead predictions of space weather phenomena such as atmospheric drag.

Thus the initial requirements analysis yielded some 35 raw requirements covering key areas such as (i) solar activity and the state of the solar wind, (ii) energetic particle fluxes and radiation dose in a variety of environments including the solar wind, radiation belts and auroral regions, (iii) the state of the auroral oval, and (iv) electron densities in the ionosphere and plasmasphere. These requirements were then analysed in terms of their applicability to each of three solution levels specified by ESA and shown in Table 2 below. Unfortunately this did not prove to be a very useful classification scheme. The vast majority of our requirements (29 out of 35) fall in level 1; this is because they are either measurements of direct interest for spacecraft operations (e.g. the energetic particle environment) or measurements of generic precursors of space weather (i.e. solar activity and solar wind state). Moving to level 2 the remaining six requirements are included by the addition of measurements needed for space weather modelling of the geomagnetic field and the micro-particle environment. Our 35 requirements do not contain any items specific to ground-based space weather applications (those are done on the ground) or to the explicit needs of science (excluded by the derivation of our requirements analysis from the assessment studies [2,3]).

Table 2. The three solution levels

| |
|---|
| **Solution level 1: Low level solution**: |
| the minimum measurements required for input to services geared at mitigating space weather effects on spacecraft operations |
| **Solution level 2: Medium level solution**: |
| incorporates all elements of the low level solution plus additional measurements of value for modelling aspects of the geospace environment and data of importance for services geared towards mitigating ground-based space weather effects (as opposed to focusing on spacecraft effects alone) |
| **Solution level 3: High level solution**: |
| incorporates all elements of the low and medium level solution plus other space weather measurements of interest to the scientific community e.g. imaging data |

The 35 requirements were then subject to a process of refinement, much of which was driven by feedback from the instrument solutions. There are three main elements in the refinement process:

1. The first was to identify cases where the sensors would be too big to be accommodated on a nanosat. This is an important issue. In many cases it is hard to reduce sensor size because of physical limitations on the measurements. A classic example is optical measurements of faint phenomena (e.g. scattered sunlight from coronal mass ejections, airglow emissions in the upper atmosphere). In this case, light grasp matters and is determined by the aperture of sensor. The size of optical sensors is also constrained by other issues such as optical system angular resolution (where aperture sets a diffraction limit), the need to match that angular resolution to detector spatial resolution (focal length ≥ detector resolution ÷ angular resolution) and the need to reject straylight when observing faint phenomena (so complex baffle systems are needed). Another area where physical limits apply is measurements of waves in the electric field for which the antenna length must exceed the plasma Debye length (i.e. the range over which electric field variations are screened), which may be of order 10m for magnetospheric plasmas. In all these cases measurements are currently made on science missions using relatively large instruments, e.g. masses of 10-40 kg and dimensions of metres. Examples include the EIT and LASCO imagers on SOHO, the TIDI Fabry-Perot instrument on TIMED and the wave instruments on WIND and Cluster. It seems likely that the physical limits discussed above will prevent sensor sizes being reduced to a level that can be accommodated on a nanosat. We have identified some 13 out of 35 raw requirements that fall in this category and have excluded them from further consideration in this study.

2. Another important area where sensor size matters is energetic particle detectors. The geometric factor of a detector sets the number of particles it will collect and thus the instrument's ability to count statistically significant numbers of particles. Sensor miniaturisation will reduce this ability and thus may compromise measurements. We have not rejected any requirements on this basis, but we have identified the critical flux level that must be measured for a number of key particle types (solar protons, radiation belt electrons, auroral electrons). Sensor size can be reduced only where it does not compromise measurements at that level.

3. The other element in the refinement process is instrument simplification. We have identified that the requirements for solar imagery contain one aspect where relatively low resolution is acceptable (90 arc-seconds, compared with a requirement of 2 to 5 arc-seconds from the RAL and Alcatel studies). This aspect is the use of solar images (e.g. at X-ray or EUV wavelengths) to detect the location of solar flares. 90 arc-second would allow flare location within a 20 by 20 grid, which is entirely adequate for assessing the geo-effectiveness of the solar proton event associated with a flare (this is greatest for flares on the west side of the Sun). As a result we have established 3 new requirements for low-resolution solar imagery, which we believe could be satisfied by a nanosat-based instrument. Another example of refinement is the use of UV photometry, in parallel with imagery, to observe the auroral oval. This offers the prospect of a more miniaturised instrument and lower data rate which will aid implementation on a nanosat. Photometry does not provide as much information as imagery but is adequate to monitor overall auroral activity and, in particular, to identify major increases in activity. With the addition in these steps, we have a final set of 25 refined measurement requirements.

The refined requirements were then assessed in terms of their appropriateness to nanosats solutions. This appropriateness was judged against two objective criteria:

1. The level of challenge in returning data, taken as the product of the data rate and the square of range to Earth. This is a useful criterion because the downlink capacity from a nanosat is expected to be constrained by available power (a few watts). The criterion value can be determined directly from the requirements, since these include the data rate and the locations at which measurements must be made.

2. The number of spacecraft needed for the ideal solution. This criterion is thought to be appropriate because a nanosat approach may facilitate mass production and deployment of spacecraft - and this favour large numbers. The criterion value can be determined from the requirements for resolution in time and space.

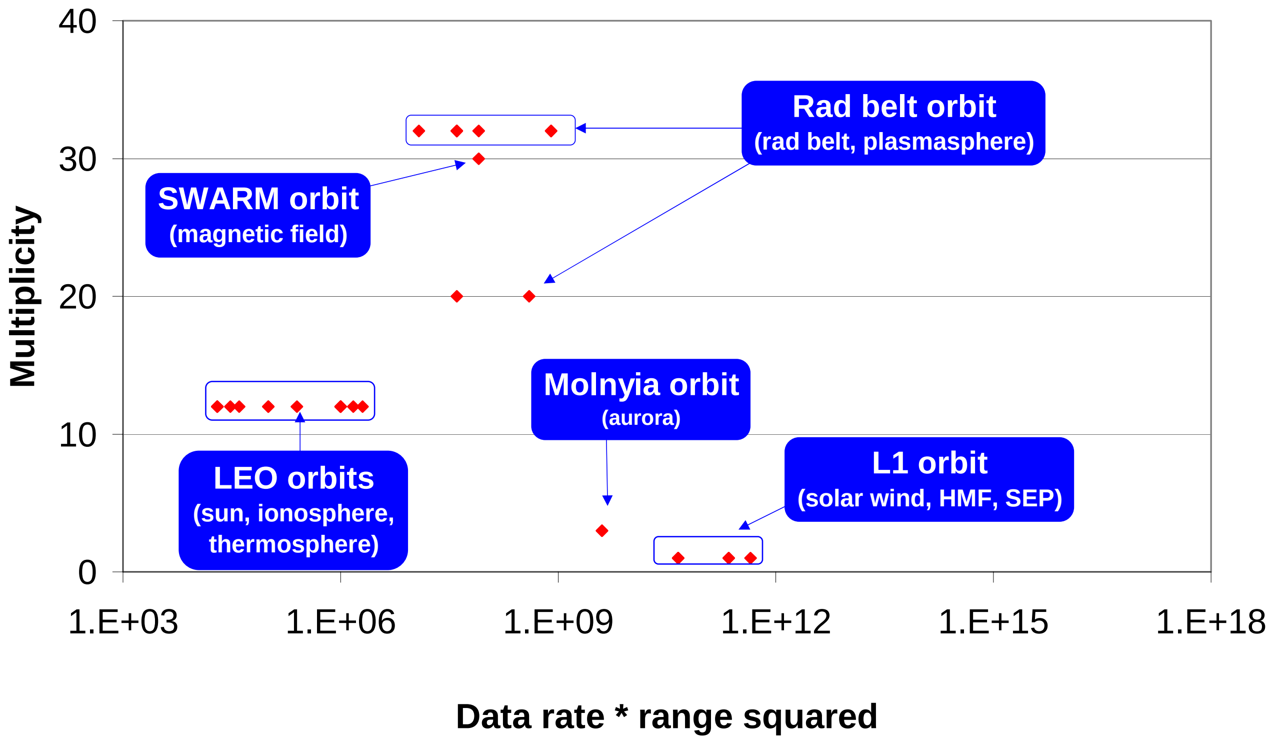


Fig. 5. Assessment of requirements by $DR^2$ (units=kbps $km^2$) and multiplicity.

The results of this assessment are shown in Fig. 5 above. Each requirement is plotted against the two criteria and is marked by a small diamond shape. They break down into five groups each of which requires a distinct constellation of spacecraft to make measurements in the appropriate regions. We regard the identification of these constellations as an important result that will be carried forward into subsequent work, especially mission analysis. The constellations are shown in Table 3 below.

Table 3. The space weather constellations (M = multiplicity)

| Location | M | Description |
|---|---|---|
| L1 | 1 | In-situ observations of solar wind, magnetic field and energetic particles at L1. Only one sampling point is required as L1 provides access to solar wind. |
| Low earth orbit | 12 | Suitable for solar, ionospheric and thermospheric observations. Use two orbits separated by 90 degrees – one in dawn-dusk plane, the other in noon-midnight. Observe sun only in dawn-dusk. The two orbits sample ionosphere and thermosphere at four local times. Use 6 spacecraft per orbit to obtain a time separation/sampling of 15 minutes. |
| Molniya | 3 | High inclination elliptical orbit (1470 x 38900km, 63.4°), suitable for remote-sensing observations of the polar ionosphere and thermosphere. The orbit period of 12h facilitates ground station coverage. This orbit is relatively stable against luni-solar perturbations. 3 s/c ensure that one spacecraft is always near apogee to make observations. |
| Rad belt | 32 | Four GTO-like orbits separated by 6 hours in local time - for in-situ observations of the radiation belts over a range of L values; multiplicity gives a resolution of 6 hours in MLT and 1 in L. Also make in-situ and remote sensing observations of the plasmasphere when inside 4 Re. |
| Swarm | 30 | A set of five highly elliptical orbits with apogee in the range 15 to 20 Re and perigee just above the atmosphere, as in proposal by Schwartz et al [8], but here used only for global study of geomagnetic field. There would be six spacecraft spaced around each orbit to give resolution over a range of geocentric distances. |

## INSTRUMENT SOLUTIONS

We have established a set of instrument solutions to satisfy the measurement requirements outlined above. These were developed by iteration between requirements and solutions, so we can be confident that we have a consistent set of requirements and solutions for implementation on nanosats. The instrument solutions have been characterised in terms of key attributes including the instrument type and heritage, the mass, power and dimensions and their likely evolution up to 2020. In a few cases we have been able to identify multiple solutions for a particular instrument and include both options in the results. It is beyond the scope of this report to provide a detailed list of instrument solutions, so we shall simply outline the main results.

Many of the instrument solutions are familiar from space plasma missions. They include fluxgate magnetometers, standard particle detectors and auroral imagers and photometers. There seems to be limited possibility for further miniaturisation in these areas except for the continuing reduction in the size of electronics. A possible exception to this is in magnetometry where new techniques are being developed such as chip-size magnetometers [9], though these would need significant development to improve sensitivity and robustness for space use. We note that the advent chip-size magnetometers would allow spacecraft, even nanosats, to fly with a large number of sensors and thus improve characterisation of spacecraft magnetic fields.

But in some areas lightweight instrument solutions seem quite feasible. These include space GPS (for sounding the ionosphere and plasmasphere) for which lightweight commercial solutions already exist. They also include dosimeter on a chip [10] and Langmuir probes [11] where test versions are ready for flight. Looking further into the future we propose a conceptual design for a lightweight solar instrument to monitor flare location with coarse (90”) resolution.

A major aim in this work has been to provide realistic targets for the miniaturisation of instrument but, if necessary, to err towards larger instruments. It is important to recognise that one must not be too definitive about instrument attributes. There is much creativity in instrument development and there is a reasonable chance that developers will deliver smaller instruments than our pessimistic assumptions. However, it is hard to turn that into a quantitative assessment. Thus we make slightly pessimistic assumptions in order to enable meaningful mission analysis.

## SUMMARY AND FUTURE WORK

This paper has outlined some key elements of the completed work on this study – namely the MNT status, the requirements analysis and instrument solutions. Significant progress has been made with the mission analysis – in particular, the analysis of the replacement strategy that is critical for an operational programme. This is driven by considerations of how the reliability of individual spacecraft impact the overall reliability of each constellation. Initial results indicate that there is limited scope to improve reliability by flying extra nanosats (i.e. through parallel redundancy) and that it is important to consider measurements to improve the reliability of individual nanosats. Existing flight experience with nanosats suggests that the present generation of experimental nanosats has low reliability and this needs to be improved before operational use.

Further work is needed to complete the mission analysis – a key issue being the analysis of payload issues now that a set of instrument solutions are available. The completion of the study will also involve establishing a high-level view on the prospects for a space weather nanosat programme and recommendations on the measures needed to enable implementation of such a programme. To support this step a small workshop was held at ESTEC following the MNT Round Table and the outputs of that workshop will be included in the study report. It is hoped to complete the study by the end of 2005 and make the final report available for public release in the early part of 2006.

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