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The NanoROLD project in the frame of the AeroClouds programme

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The article reports on the study results of the NanoROLD (Nano Radio Optical Lightning Detector) project, which was proposed for inclusion in action line 3 (Climatic aspects of clouds and precipitation) of the AeroClouds Programme planned around the year 2004 by the MIUR (Ministry of Education, University and Research). After a short review of the AeroClouds objectives and the lightning geolocation requirements, the article reviews the location accuracies achievable with both single and multiple satellite system configurations, and compares the two approaches from performance and complexity viewpoints. The feasibility of radio frequency (RF) detection of electrical discharges is dealt with first, to demonstrate the feasibility of a high accuracy lightning geolocation mission by means of microsatellites, while the assessment of optical instruments is deferred to a later study phase. The final comparison is then restricted to two candidates: a three-satellite formation exploiting time-of-arrival (TOA) principles; and a single satellite implementing a three-arm radiofrequency interferometer. The expected greater costs of a three-satellite constellation in formation flight are offset by the greater complexity and criticality of the interferometer system based on a single satellite and by its poorer performance in terms of lightning geolocation accuracy. However, for an experimental, fund-limited programme, a demonstration mission based on a single satellite could be more appropriate and an initial baseline design is also provided in the article.

1. The AeroClouds programme

AeroClouds was intended to be a three-year programme with a budget of about €5 million. The project involved several Italian research institutions, led by the Institute of Atmospheric Science and Climatology (ISAC) of the National Research Council (CNR) and including the University of Ferrara, the University of L'Aquila, the University of Urbino and the National Agency for Energy and Environment (ENEA).

The basic goal of the AeroClouds project was to investigate the direct and indirect effects of aerosols and clouds on the climate. Atmospheric aerosols are the cause of

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absorption and scattering of both incident solar radiation and infrared radiation emitted by the Earth's surface and, in this respect, they govern the thermal budget of the Earth–atmosphere system. On the other hand, cloud formation can strongly impact the thermal budget by reflecting the incident solar radiation and absorbing the Earth's infrared radiation, depending on the microphysical, chemical and radiative properties of the cloud itself. Precipitation from clouds and its distribution is another major piece of the global mosaic.

Over the years the role of clouds and aerosols on the Earth's climate has sparked increasing interest. Amongst others, we mention the International Geosphere-Biosphere Programme (IGBP), where 72 nations adhere on the topics of global change; the project IGAC (International Global Atmospheric Chemistry); and the working groups of the Intergovernmental Panel on Climate Change (IPCC).

Following the above initiatives and issues, the AeroClouds project was subdivided into four main lines of action: (1) radiative properties of aerosols – direct climatic effects; (2) aerosol–cloud interactions – indirect climatic effects; (3) climatic aspects of clouds and precipitation; and (4) modelling aerosol effects on climate at a global and regional scale.

The NanoROLD (Nano Radio Optical Lightning Detector) project was intended to become part of action line 3, dealing with new space missions and advanced sensors. Its main goal was to analyse the feasibility of a hybrid sensor on board a constellation of micro-satellites for detecting and localizing the lightning activity from space. This article, which summarizes the work performed by the authors after the first published results (Perrotta *et al*. 2004), discusses some target operational requirements for the radio frequency (RF) detection of electric discharges and deals with the preliminary definition of satellite systems able to provide an answer to such requirements. The assessment of the feasibility and convenience of adding an optical instrument is deferred to a later study phase.

2. Lightning localization needs

There is experimental evidence that global lightning activity provides a measure of large-scale temperature variations associated with climate change. In addition, quantitative relationships have been proposed to relate flash rates to rainfall intensity. Research efforts to investigate the processes involved in the evolution of convective systems, through the characterization of regions where dynamic and microphysical processes can sustain electric activity, are under way. In this direction, the experimental data obtained by the FORTE satellite, and the ensuing analysis, have greatly contributed to the understanding and characterization of lightning.

With FORTE both optical and RF instruments were used to capture the lightning events' emissions in the visible and very high frequency (VHF) bands, respectively. Looking at previous experiments concerning the gathering of radiowaves and optical emissions from electric discharges, the technology-related advances achieved in the last decade can be summarized as follows:

- improvements in instrument sensitivity from lightning Effective Radiated Power (ERP) values of 10^5–10^3 W;
- capability of localizing thunderstorms to within several hundred kilometres;
- capability of performing electrical discharge wideband RF spectral analysis; and
- capability of separating in time events separated by a few microseconds.

The large amount of data provided by FORTE (Jacobson *et al*. 1999) shows, however, certain limitations, such as a lack of precise geolocation of the events, a limited correlation between optical and RF emissions, and a weakness of the optical sensors in detecting lightning in daylight and over oceanic areas. As a result, the attention of researchers is now moving in several directions, one of which concerns ways to improve the lightning geolocation accuracy, in 2D and 3D.

The contribution from lightning mapping and data acquisition to the understanding of geophysical phenomenology has led to the early conception of operational lightning mapping space systems (Suszcynsky *et al*. 2006), based on Medium Earth Orbit (MEO) constellations. However, the same service can be implemented with Low Earth Orbit (LEO) constellations (Lalande *et al*. 2003). In this context, this article illustrates the rationale and key characteristics of possible experimental systems – as forerunner of an operational one – based on microsatellites in LEO aiming at providing better 2D, or even 3D, lightning geolocation. Though a combined RF–optical sensor complement can be installed on a microsatellite system, this article will concentrate on the RF collection of the electrical discharge emissions in the most promising frequency bands.

Improving 2D lightning geolocation is the first priority of this project. A spatially distributed system appears a good solution to the problem; however, to better illustrate advantages and drawbacks of several candidate solutions, we provide a brief trade-off centred on the main problem of how to geolocate a lightning event: (*a*) using only one satellite; and (*b*) via a constellation of satellites flying close together in near-formation.

3. Geolocation with one satellite only

We will assume that the satellite is nadir-pointed during its normal operation and is equipped with a fairly performing attitude control system.

3.1 *The FORTE approach*

A rather simple approach to geolocating a storm was tested with the FORTE satellite (Jacobson *et al*. 2002). We recall that FORTE is equipped with a dual polarization antenna, intended to measure the lightning's power, frequency of occurrence, polarization characteristics of the RF emissions and their temporal profiles, and the spatial distributions of storms for statistical analyses: the cueing to the occurrence of an event being given by optical sensors.

The technique adopted to track a storm consisted of recording sequentially the angle of arrival of multiple lightning events originating within the same storm by exploiting the polarization properties of the FORTE payload antenna. By so doing, it was possible to geolocate a storm in a region of approximately 250 km radius – thus, rather coarse. Besides this, there was an ambiguity problem in the geolocation that needed to be solved by other means.

The main problems with the FORTE method are its dependence on polarization and type of antenna – thus lacking generality; the coarseness of the geolocation; difficulties in adopting the polarization-based angle-of-arrival determination for certain lightning types; generating randomly polarized RF emissions; and the abovementioned geolocation ambiguity. All these emphasize the need to look for alternative approaches.

3.2 *Geomagnetic birefringence*

One method to geolocate an electric discharge event is by exploiting the geomagnetic birefringence (Jacobson and Shao 2001). The technique is based on the detection and measurement of the frequency characteristics of the emissions of multiple lightning events, occurring within the same stormy area, received by the satellite in different positions of its orbital path. In essence, one attempts, again, to exploit the time-variable relative position of the satellite with respect to the stormy area to grossly geolocate it.

However, the method, based on geomagnetic birefringence, seems even more complex in terms of signal processing than the FORTE system described in Jacobson and Shao (2001), and is also more questionable concerning data reliability and service availability because of its dependence on the geomagnetic field orientation with respect to the spacecraft attitude and orbital position. Accordingly, in our study this method was excluded early from the list of candidates.

3.3 *Amplitude monopulse*

One way of geolocating the RF emissions is based on a classical amplitude monopulse system operating in the receive mode: four identical antennas are installed on the satellite with their boresights angularly displaced with respect to the nadir. By performing, at RF, the sum and difference of the signals received by pairs of opposite antennas and processing the resulting signals, it is possible to compute the radial and azimuthal components of the angle joining the satellite with the lightning radio emission.

Geolocating the event requires knowledge of the satellite position (which is known since the satellite will be equipped with a Global Positioning System (GPS) receiver), of the satellite instantaneous attitude (this requires, instead, a very accurate attitude determination system on board) and of the orbit plane with respect to the Earth. With this method one cannot achieve a lightning geolocation in 3D; in fact, the electric discharge event can occur anywhere along the line joining the satellite with the event 'projection' onto the curved Earth.

The geolocation error depends on the antenna system difference slope, the signal-to-noise ratio, the residual satellite pointing errors, and propagation errors (such as ray bending) – which may become important for large off-nadir angles – plus other bias-type errors. One contribution to the latter depends on the stability of the difference patterns, which may change slowly but consistently due to environmental factors causing both mispointings of the four beam boresights and of the beamshapes. Since the RF wavefront arrives simultaneously at the four antennas, timing errors can be, instead, disregarded.

Typically, the geolocation error will be contributed mostly by satellite attitude stability. With a satellite at 500 km altitude, a 20 dB signal-to-noise ratio, a spacecraft attitude error of 0.5° – which is, however, hardly feasible with a small satellite carrying large and flexible VHF antennas – and an in-orbit antenna pattern stability of 10%, the random geolocation error is of the order of 5 km at the edge of coverage, with a bias-type error around 6–8 km. This is a significant improvement with respect to the FORTE approach. Nevertheless, the physical implementation of the four antennas is of concern since, to provide a significant gain, they cannot be small, thus impacting the satellite mass, stability and ease of control.

3.4 *Interferometry*

An alternative method for 2D lightning geolocation is based on interferometry. With this approach, the satellite would be equipped with a minimum of three identical antennas (antennas A, B, C), all nadir-pointed and put on the tip of booms protruding from the satellite to form a nearly equilateral triangle with a side of length S m. The geometry is defined in figure 1.

x, y, z is a reference system arbitrarily chosen to have the x-axis parallel to the satellites' orbital plane, the y-axis orthogonal to it and the z-axis along the local zenith. The x–y plane is tangential to the orbit path and, obviously, orthogonal to the zenith. Antenna A is put at the origin of the reference axes. The vector joining the lightning discharge L with the satellite A is characterized by the angles θ and ψ. A plane wavefront generated by a lightning event L and arriving at the satellite, will reach the antennas phase centres with different phases. By measuring the three phase differences A to B, B to C and A to C, it will be possible to estimate the radial and azimuthal components ψ and θ of the angle joining the satellite with the lightning radio source. The main problem with interferometry is that it was originally intended for operation with nearly narrow-band or continuous wave signals. In the presence of wideband signals the phase differences will vary, potentially causing large errors in geolocation. One could attempt to compute the phase differences at the bandwidth extremes and band centre and make an average, or else pass the signal in a narrow bandpass filter and perform the phase difference at that frequency, provided that the RF spectrum of the incoming signal has sufficient energy content in that specific frequency slot to achieve a good signal-to-noise ratio.

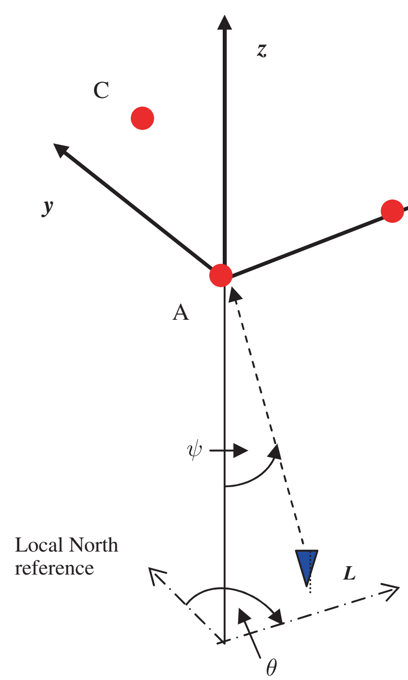

Figure 1. Lightning event to satellite coordinates.

A second problem concerns the measurement quantization: 1° means relying on a signal-to-noise ratio better than 35 dB, which is hardly feasible. A more realistic – though still a bit optimistic – value for the signal-to-noise ratio is 20 dB, which is about 5° resolution. A third problem is the baseline length, which impacts directly on the location error. Indeed, the estimation error $\Delta\psi$ on the angle of arrival is given by:

$$\Delta\psi = \lambda / \left(\pi D \cos\theta \sqrt{(S/N)}\right) \tag{1}$$

in radians, where λ is the wavelength at the operating frequency and S/N is the signal-to-noise ratio.

Though a short baseline D, say of the order of 1 m, would be preferred for the stability of the microsatellite, a longer baseline is nevertheless needed to decrease the geolocation error induced by bias and random errors in the differential phase evaluation.

With a 5° measurement quantization error, a 3 m interferometer baseline and at nadir, the error in the angle of arrival estimate $\Delta\psi$ is 0.6° at 30 MHz and 2.54° at 70 MHz. The impact on the lightning geolocation will then be – for a satellite at 500 km altitude and for a lightning event occurring close to nadir – between 5.2 km at 30 MHz and 22 km at 70 MHz.

Clearly, carrying out the differential phase measurements in a narrower frequency slot at the lower edge of the analysis bandwidth would lead to a smaller geolocation error, if the signal energy is sufficient to guarantee a signal-to-noise ratio above 20 dB, which was discussed earlier as the target value. The other error contributions, such as those due to propagation, satellite attitude stability and knowledge of spacecraft orbital position, are similar to those discussed for the 'amplitude monopulse' approach, with the difference that the antenna system is a bit simpler and, therefore, the satellite attitude error can be controlled in a better way and possibly in the 0.1° range, which will cause a geolocation bias error of the order of less than 1 km in the worst case, at edge of coverage. Accordingly, it is estimated that an overall geolocation error could possibly be kept within 5–10 km by operating in a narrow band close to the lower edge of the analysis bandwidth, and by suitably optimizing the phase detection and measurement system, while improving the spacecraft attitude control system.

The main concern with the interferometer solution is the length of the telescopic booms that would have to support the three nadir-pointed antennas, which impact on the spacecraft configuration. However, AEC–ABLE (1993), Derbes (1999) and Davies *et al*. (2004) provide hints on how to possibly solve the antennas' stowage problem. In summary, the interferometric approach seems a promising solution, worth further consideration.

3.5 *Time of arrival*

Another method sees the interferometric system replaced with a time-of-arrival (TOA) one. The physical configuration with three nadir-pointed antennas will remain the same as that used for interferometry, but instead of measuring the phase difference of signals received by antenna pairs, the system measures the time differences of the pulse wavefronts hitting antenna pairs.

The main problem with the TOA approach with limited baseline length is the sensitivity, which is too poor. Indeed, for a baseline length L of 10 m – already very challenging in terms of implementation on board a microsatellite – one has a resolution of 0.6 ns per degree of wavefront offset for events close to the satellite nadir, decreasing to 0.4 ns per degree for events 40° off-nadir. With a timing quantization of 5 ns (somewhat challenging for space implementation, from both a cost and power drain viewpoint), the projected geolocation error on the ground – due to the measurement granularity only – would not be less than 80 km at nadir and 120 km at 45° off-nadir for a satellite height of 500 km. Other causes of error stem from propagation, timing jitter, signal-to-noise ratio and environmental causes (e.g. temperature) impacting the differential time delays in the various signal paths.

Thus, even though the system is conceptually less sensitive than the interferometric one to satellite pitch and roll attitude errors, the limited baseline length feasible with a single satellite can lead to geolocation errors of several hundred kilometres. On top of this, other physical implementation problems, such as the placement of antennas on the satellite, in both the folded and on-orbit deployed configurations, will have to be considered.

4. Geolocation with multiple satellites

Both the interferometric and the TOA systems would benefit from a dispersion of the space-based sensors over a wide area (Koshack and Solakiewicz 1996). However, since the TOA approach is less prone than the interferometric one to satellite-induced errors, it is preferred for a space-distributed implementation.

A constellation of three satellites spaced widely apart – as shown by the three circular dots in figure 1 – and each equipped with only one antenna allows one to geolocate an individual lightning event with a 2D resolution in the 1–10 km range, depending on the constellation topology. Such an improvement in 2D geolocation accuracy, with respect to that achieved by FORTE, supports the characterization of intra-clouds (IC) discharges.

The performance advantages of installing sensors on spaced-apart satellites increase with the mutual distances. Indeed a large baseline length can be achieved easily in space-distributed systems. For a baseline length of 30 km, the TOA sensitivity is between 1.73 (for $\delta = 0$) and 1.1 (for $\delta = 40°$) $\mu s/°$, where δ is the angle of arrival of the lightning wavefront with respect to the baseline normal. For a timing quantization of 20 ns and 500 km orbital altitude, the geolocation granularity resolution will be 0.11 km at nadir and 0.2 km at 40° off-nadir.

The nominal constellation would consist of three satellites at the vertices of a triangle with, nominally, 30 km sides. This configuration might be left free to evolve in time under the effect of external forces or else a formation flight could be enforced. In the latter case the algorithm for geolocating the electrical discharge from the TOAs can be simplified. On the other hand the advantage of not forcing the satellites to fly in formation leads to simplifications in satellite design and constellation management, but the computation for geolocating the discharge becomes more complex.

As a matter of fact the triangle, on the vertices of which are put and maintained the three satellites of the constellation, does not necessarily have to be equilateral nor do the satellites have to be kept in the same plane. Indeed, the calculation of the angle of arrival of the RF wavefront – generated by an electrical discharge event – using the TOAs at the three satellites, can be performed for whichever satellite topology. This is provided that the instantaneous position of each satellite in 3D is known (e.g. from the onboard GPS receiver) with respect to a known Earth reference and that the constellation topology avoids singularities, such as an alignment of all three satellites. The algorithm required to cope with a full variability of the triangular geometry is a bit more complex than in the simpler case where the equilateral triangular configuration is maintained throughout the mission.

The geolocation error budget includes the following terms:

- the timing granularity error, which is very small as discussed earlier;
- the propagation errors, which are not quantized here but are assumed to be of the same order of magnitude as in the single-satellite case;
- the attitude errors, which are negligible. Indeed, the multiple satellites' TOA approach is not affected by attitude errors because the satellite antennas phase centre is not significantly displaced. This greatly simplifies the satellite design; and
- errors in the satellites' position restitution: a ± 12 m position error in the estimate of each satellite spatial position leads to a geolocation error of between 0.2 and 0.3 km.

All these error sources amount to less than 1 km uncertainty error. Accordingly, the deviation from the parallelism of the line-of-sight joining the discharge with the three satellites will then become the largest error source if not corrected. The software for reconstructing the lightning origin will then have to take into account Earth's sphericity, as discussed by Koshack and Solakiewicz (1996).

5. Comparison summary

The key features of the lightning geolocation methods assessed in our study are summarized in table 1, which includes an assessment of the implementation aspects, such as risk and technology maturity and complexity. As a result, two candidate solutions were studied in more detail: (1) a single satellite implementing a 3 m baseline interferometric system; and (2) a constellation of three satellites implementing a TOA approach with a 30 km-side triangular baseline.

The first seems better suited to an experimental phase, aiming at an overall 'target' geolocation error in 2D of around 10 km. The second solution is more representative of an operational space segment configuration based on multiple satellites in MEO or LEO, aiming at an overall geolocation error in the 1–5 km range. More effort is, however, necessary to ascertain the relevant total system costs for designing, developing and launching a single satellite carrying three large VHF antennas, in-orbit deployable and characterized by a high performance three-axis attitude control subsystem; and that of designing and developing, launching and maintaining in-orbit three microsatellites each equipped with only one deployable antenna and a much simpler attitude control system. In the following section, we provide additional elements to support the comparison.

6. Single-satellite system architectural design

The space segment will consist of a single microsatellite. The orbit will be circular with an altitude around 550 km and inclination in the 50°–60° range for a good coverage of the tropical–temperate and subpolar latitude belts. Accordingly, the RF sensor has at least one chance a day of overpassing any point on Earth within the $\pm 60°$ latitude belt.

Table 1. Comparison of prospective lightning geolocation methods.

Satellite system	Event detection method	Number of antennas	Sensitivity to attitude errors	Number of receivers and complexity	Lightning geolocation performance	Perceived technology risk
FORTE (single satellite, single antenna)	Received signal strength and polarization	One, log-periodic, nadir-pointed	Small but not negligable	One multiband receiver	Order of 250 km radius	Medium
Single satellite, single antenna	Geomagnetic bi-refringence	One, nadir-pointed	Probably not negligable	n.a.	Dependent on latitude and satellite attitude	Unknown
Single satellite, multiple antennas	Amplitude monopulse	Four, with beam crossover of 3–6 dB	Very high	Four, quite complex and critical	Several hundred km, due to bias and time-variable errors	Very high
Single satellite, multiple antennas	Interferometry	Three, nadir-pointed; baseline length of 3 m	High; three-axis stabilization needed with less than 0.1° pointing accuracy	Three high performance receivers	Order of 10–20 km depending on frequency	High
Single satellite, multiple antennas	TOA of incoming wavefront	Three, nadir-pointed; baseline length > 3 m	Somewhat less critical than for interferometry	Three medium–high performance receivers	Rather poor geolocation performance (baseline length limited!)	Medium–high
Constellation of three satellites	Interferometry	One, nadir-pointed per satellite. Baseline length about 30 km	Rather small	One (two channel) per satellite	Order of few km with a baseline length of 30 km	Medium–high
Constellation of three satellites	TOA	One, nadir-pointed per satellite. Baseline length about 30 km	Very small	One (two channel) per satellite	Order of few km with a baseline length of 30 km	Low–medium

The evaluation of the geolocation of each individual lightning event perceived by the satellite will be computed both onboard and by the Mission Control Centre (MCC) upon the deferred-time reception of onboard stored data. To this end, the satellite will be provided with an appropriately sized onboard memory to store both raw and pre-processed data. Data dump to ground will occur in the S-band at a data-rate set in the 256 kbps to 2 Mbps region.

The ground segment will initially consist of a single Earth station performing the functions of an MCC, Telemetry and Tracking Centre (TTC) station and data receiving station in charge of decoding and routing via the Internet, the science data transmitted by the satellites. An expansion of the ground segment is expected, with additional receive-only stations world-wide located at the premises of science groups interested in receiving and elaborating the data captured by the satellite.

6.1 *Single-satellite RF payload main characteristics*

The RF payload borrows some characteristics from FORTE, though it narrows the analysis bandwith to the 30–70 MHz range. The capability of inferring the polarization characteristics of the emitted RF pulse is also maintained. On the other hand, some onboard pre-processing functions, such as spectrum whitening and dechirping, are not planned to be performed onboard, but are left to on-ground processing.

The most important difference from FORTE is the antenna farm, which consists of three single polarization log-periodic antennas, each with seven elements operating in the 30–70 MHz band, where the bulk of the lightning emissions occur. A reduced antenna gain from 10 to about 6 dB is consistent with a 550 km altitude orbit, which provides the same beam footprint as FORTE. The three single polarization antennas have the plane of their dipoles rotated by 120°; therefore, for a generically polarized incoming wavefront the three antennas will provide a response depending on the radiation pattern and orientation of the dipoles with respect to the polarization plane.

From the interferometric measurements, the angle of arrival of the lightning wavefront is estimated with fairly good accuracy; besides, the antenna patterns can be measured on the ground before launch and are not expected to change appreciably during the satellite operational lifetime. From these data, a real-time estimate of the polarization of the incoming wavefront can be performed.

The operation of the interferometer is implemented via three analogue phase detectors; the input signals are amplified and clipped to eliminate amplitude imbalances, while enhancing the phase features. Although two measures are necessary, the third being linearly dependent on the other two, nevertheless all three measurements are performed both to cope with unlikely blind polarizations and to increase the probability of having at least two ‘good’ measurements.

The payload block diagram is shown in figure 2. Three channels, each fed by a log-periodic antenna, can receive on either one of the two sub-bands: 30–50 MHz and 50–70 MHz. The up-conversion frequencies to bring the channels to an intermediate frequency (IF) in the L-band are provided by a frequency generator, which outputs also the down-conversion frequency to bring back the IF signals to baseband. The path that the video signal follows consists of two parts: one goes to a bank of amplifiers, clippers and analogue phase comparators, where the phase differentials between channel pairs are measured; the other goes to a circuit that performs the geolocation estimate of the electrical discharge.

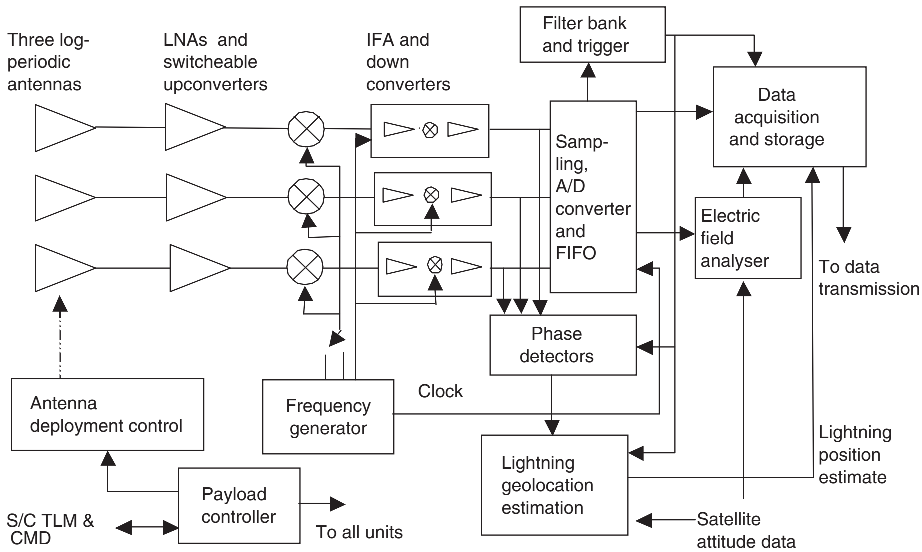

Figure 2. Single-satellite system payload block diagram. LNA, low noise amplifier; S/C, spacecraft; TLM, telemetry; CMD, command; IFA, intermediate frequency amplifier; and A/D, analogue to digital.

Concerning the signal amplitude processing, all three video signals are sampled at 50×10^6 samples per second, at 12 bits/sample, and sent to three First-In-First-Out (FIFO) memories of about 1 megabit each. In parallel to the signal digitization and temporary memorization in FIFOs, a triggering circuit is active, with the purpose of discriminating the occurrence of real impulsive lightning emissions from background and anthropogenic noise. To this end, a simplified implementation of the FORTE circuit is envisaged with a reduced, but selectable, number of low-pass filters and a possibly adaptive trigger threshold. In the event of no output from the trigger circuit, the data in the FIFOs are progressively discarded and replaced by new ones. When a trigger arrives, part of the data already in memory and the data arriving over an interval that can be preset, are passed onto a mass memory. The length of a typical record is less than 1 ms, and the mass memory has a capacity to store at least 1000 events on the three channels, plus ancillary data, for a total of about 4 Gbit. The three data samples are also processed, via a suitable algorithm, for characterizing the polarization properties of the electric discharge and the result is added to the raw data stored in the mass memory.

To keep the satellite simple and cost-effective, all important data processing, relevant to the lightning spectrum content and pulse waveform, is proposed to be performed on the ground, taking advantage of the more powerful technical means available in the MCC, with the exception of the lightning geolocation and polarization characterization, which will be implemented onboard using only part of the computing resources of the satellite computer.

6.2 *The payload antenna farm*

The antenna farm plays an outstanding role in determining the performance of the single-satellite lightning observation system. An artist's view of the satellite's antenna farm after the in-orbit deployment is given in figure 3.

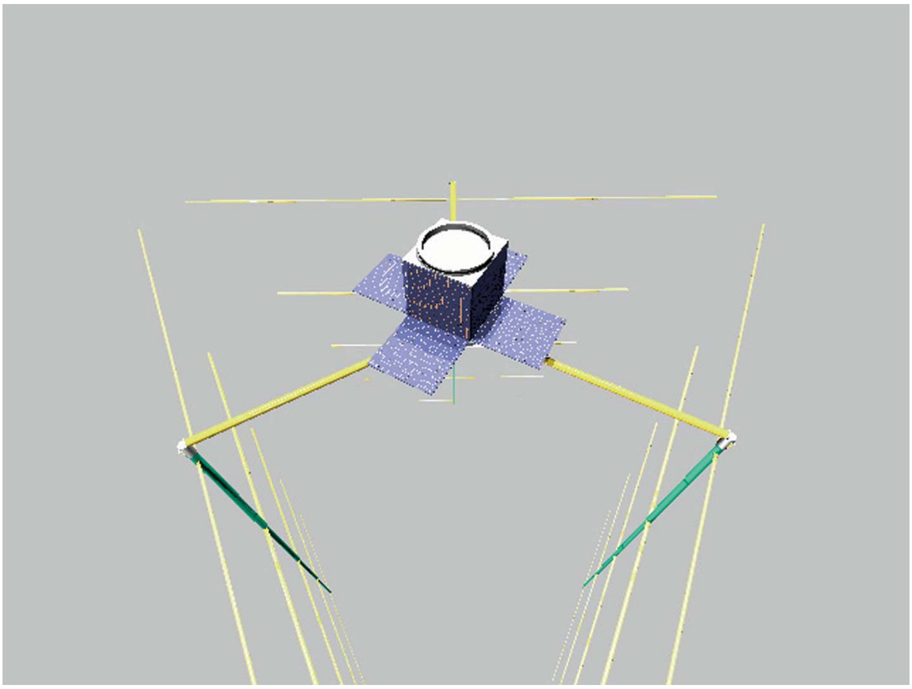

Figure 3. Artist's view of the satellite antenna farm deployed in orbit.

During launch the telescopic booms are stowed in a retracted configuration. Tubular telescopic deployers are used for each antenna. The tubular element deployer technology is known and has been flown in many satellites; but for this application a very compact and lightweight design will be needed. The telescopic mast providing the relative spacing between the dipoles has six sections.

For the radioelectric design, reducing the overall boom length was a key requirement, thus the antenna parameters $\tau = 0.12$ and $\sigma = 0.8$ were chosen (τ is the ratio of one element length to the next longer neighbour; σ is the relative spacing constant), which led initially to a five-element log-periodic antenna, then increased to seven-element to improve the pattern shape in the upper half of the bandwidth, resulting in an overall deployed boom length of 5.2 m. Patterns in the presence of the other two log-periodic antennas, terminated on a 50 Ω load and simulating their in-orbit relative orientation and spacing, were computed, using the NEC_WIN plus software.

To assess the effect of mutual coupling, figure 4(*a*) shows the computed antenna patterns in the absence of mutual coupling, while figure 4(*b*) shows the same pattern cuts in the presence of mutual coupling. From these, the impact of mutual coupling on gain and beamshape at three frequencies can be seen clearly.

The impact of mutual coupling is more tangible in the lower half of the design bandwidth, but is not the cause of much concern. In addition, an increase in the inteferometer baseline from 3 to 4 m is also being considered.

6.3 *The satellite's main characteristics*

There are a number of satellite features resulting from an initial assessment of the science and operational objectives.

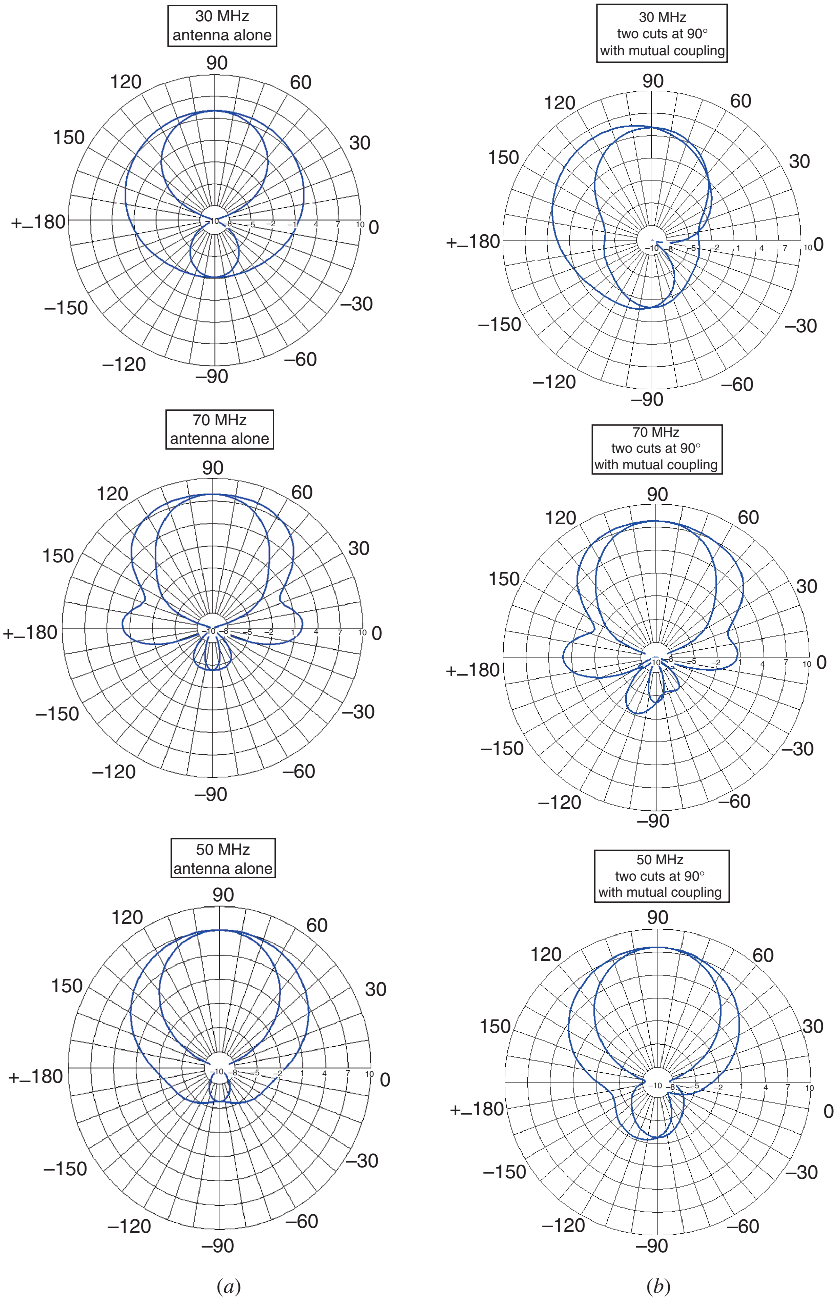

Figure 4. Antenna patterns (*a*) without mutual coupling and (*b*) with mutual coupling.

- The satellite body will consist of a stack of four mechanically linked modules separately assembled and testable: propulsion, service, payload and antenna farm.
- The first three modules have overall dimensions of 450 mm × 450 mm × 450 mm for an allocated mass of 40 kg, propellant excluded. The antenna farm, in the

launch configuration, will stay within an envelope of 60 cm diameter by 130 cm height. The mass allocated to the antenna farm is of the order of 35 kg.

- Orbit control: as a baseline, the satellite will not carry a propulsion system for a projected lifetime of three years. If a longer lifetime is eventually chosen, then a small propulsion system, based on resistojets, may be included in the propulsion module.
- Thermal control, which will be based mainly on passive techniques, will be managed in the service module but sensors and actuators will be spread where needed.
- The service module includes all other subsystems necessary to support the payload operation throughout the nominal lifetime.
- Attitude control. The satellite nominal attitude will be nadir-pointed. For attitude determination, Earth-sensor, magnetometers and GPS-provided orbital data are envisaged. Attitude control is by magneto-torquers and a pitch momentum wheel.
- Orbit position determination and absolute timing is via a GPS receiver onboard.
- Power generation and energy storage. Electric power will be generated by four body-mounted and four in-orbit deployed panels. The installed gallium-arsenide cells' area will be around 1.3 m^2. However, the effectively available direct current (DC) power on the 60° inclined orbit will vary during the orbit period and will be substantially less than that corresponding to the installed cells' area. When in the Earth's shadow the satellite will be supported by rechargeable lithium-ion batteries.
- Command and telemetry in the S-band; downlink telemetry capability: multi-rate, 256 kbit per second to 2 Mbit per second, in binary phase shift keying (BPSK). The projected total visibility time for science data downloading during any 24 hours is around 15 minutes (per ground station), corresponding to a downloaded data volume of 1.8 Gbit at the higher downlink data-rate.
- Data handling: since most of the analyses on the received lightning pulses will be performed on the ground, the onboard memory has to cope only with rather modest data storage requirements, for which a 4-Gbit solid-state memory is baselined.

7. The constellation system architectural design

The space segment will consists of three identical microsatellites in formation flight in a plane tangential to the orbit, and put at the vertices of a triangle with a nominally 30 km side. The allowed relative position error with respect to their nominal position is around ±12 m in all directions. The orbit's altitude and plane laying are the same as for the single-satellite system. The satellite carries a somewhat simpler RF payload, equipped with one VHF antenna only and a much less critical attitude control system. However, it also implements a quite simple intersatellite link to exchange position, housekeeping and science data with the other partner satellites.

The ground segment is, in principle, the same as that outlined for the single-satellite configuration, the only difference being in the multiple, though non-simultaneous, handling of all three satellites in formation instead of only one.

7.1 *The payload antenna*

The RF payload antenna, in the constellation system, will be a crossed dipole log-periodic, as in FORTE; however, the dimensions will be those determined for the single-satellite configuration discussed previously in section 6.2, i.e. a seven-element log-periodic antenna with an overall deployed length of 5.2 m for a gain between 5 and 7 dB depending on frequency. The mechanical implementation of the antenna will consist of a motorized multi-section telescopic dielectric mast with an inner diameter sufficient to carry the tubular elements deployers, four per section, required to implement the crossed dipole log-periodic antenna. In the launch configuration, the antenna will look like a circular tube of nearly 1 m length and 15 cm diameter, protruding from the cube-like microsatellite Earth-facing panel, while a deployment motor will be housed inside the satellite body. In orbit, the antenna will contribute to the creation of moments of inertia favouring a gravity-gradient satellite attitude stabilization, which can be further increased, if needed, by adding mass on the telescopic boom tip.

Indeed, with the space-distributed TOA approach, the satellite attitude control can be rather coarse, say in the 2°–5° range, which can be achieved via a low-cost gravity-gradient attitude control, possibly aided by a damping device and magnetic coils both as a measure against attitude ambiguity problems and to speed up acquisitions.

The log-periodic antenna patterns are essentially the same as those reported on the left-hand side of figure 4(*a*) and are highly symmetrical. Indeed, the lack of mutual coupling is a positive feature here both to simplify ground testing and the beam pattern characterization, and to simplify the reconstruction of the lightning's electric field polarization characteristics from the received signals on the two orthogonal channels.

7.2 *The RF payload features*

The payload for the configuration with three satellites in formation flight (figure 5) is simpler than that shown in figure 2, although certain blocks are similar and have equivalent functions, such as:

- the frequency generation and timing;
- the electric field polarization analyser (though implementing different algorithms);
- the filter bank and trigger circuit, which signals the arrival of a probable lightning wavefront and starts both the timing counting and the acquisition of the incoming signal trail;
- the data acquisition and storage circuit;
- the interfaces with the satellite GPS receiver for the universal time; and
- the interface with the spacecraft data handling subsystem for data transfer to/from Earth.

The main differences are:

- the receiver has only two channels (one per polarization) instead of three;
- the data acquisition and storage section interfaces an intersatellite link (ISL) for the exchange of the TOA data measured at each satellite and their spatial positions. These data are used to geolocate the lightning. To this end, one of the three satellites (or else all of them for redundancy) are equipped with a processor-based circuit where the three TOAs and the GPS-derived spatial position of each spacecraft are input to an algorithm which takes into account the Earth's sphericity to predict the spatial origin of the electric discharge.

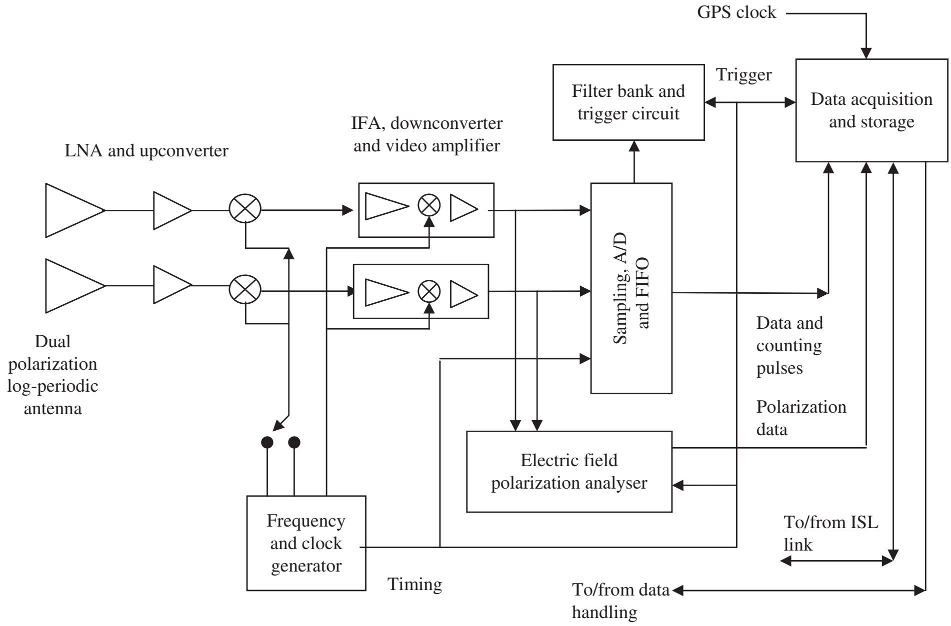

Figure 5. TOA-based constellation: payload block diagram.

7.3 *The satellite's characteristics*

The main differences between the microsatellite hosting the payload and antenna tailored to the operation in the spatially distributed TOA mode and that hosting the three antennas in the interferometric system described in section 6 are related to the differences in the antenna layout and dimensions and to the different requirements in terms of spacecraft attitude control.

The other subsystems are almost similar with the exception of the addition of an ISL package for two-way data exchange amongst the three satellites of the formation. The ISL package must support both low and high data-rate for transferring the memory content or part of it to one or more of the partner satellites to support onboard processing operations.

In any case, the ISL must be implemented over distances of the order of 30 km; therefore, relatively low transmit powers are needed. The use of millimetre waves, or even optical frequencies, can be considered (Perrotta 2006) to keep the ISL package dimensions within tight limits.

8. Conclusions and outlook

Two different space system concepts to achieve a more precise geolocation of individual lightning occurrences during thunderstorms were presented and discussed. One is based on a single but quite complex microsatellite implementing an interferometric measuring system of the angle of arrival of the RF wavefront emitted by the electrical discharge. The other is based on a constellation of three identical microsatellites in formation flight implementing a space-based TOA measurement system to geolocate the lightning.

Relative geolocation errors were estimated and compared as well as the differences in the payload and antenna system characteristics and how these are reflected in the satellites' complexity and criticality.

Future activities will have to look in depth at the antenna implementation aspects, with special attention given to motorized or spring-actuated mechanisms. Also of concern – for the single-satellite system – is the performance of the phase detector in a time-variable noisy environment, and the adequacy of the 3 m interferometer baseline length, which could possibly be increased to 4 m. The polarization features and stability of each log-periodic antenna, in the presence of the mutual coupling caused by the other two, needs to be better analysed to assess the limits of the lightning's polarization characterization. The trade-offs concerning the extent and depth of onboard processing functions, such as spectrum whitening and dechirping, may also require critical revision.

For the three satellites in formation flight, the aspects worthy of further investigation are the requirements for data exchange between satellite pairs which impact the ISL package solution, and the alternatives, if any, to the dual polarization log-periodic antenna.

As a result of refinements to the configuration trade-offs, more precise cost estimates could be produced, thus making easier a possible choice between either configuration for a prospective experimental mission.

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