GRAVES: The new French System for Space Surveillance

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ABSTRACT

The GRAVES system is a space surveillance system developed by the French Aerospace Research establishment (ONERA) under contract from the French MoD. It consists of a specific radar sensor associated with automatic data processing software which creates and maintains a catalogue of the orbital parameters of the detected satellites.

The key driver for the development was to produce a low cost system in terms of development and maintenance. It led to an original concept of a full electronic scanning bistatic CW sensor, operating in VHF, using Doppler detection and digital beam forming reception technique.

On the other hand, great effort has been devoted to the development of the software that converts the raw measurements of the sensor into an orbital parameter catalogue. This was a very demanding challenge because this software has to deal with rather "poor" measurements which came from a unique radar sensor.

1. ACRONYMS

COTS: Commercial Off The Shelf
DMS: Data Management System
ESO: European South Observatory
GEO: Geostationary Earth Orbit
GRAVES: Grand Réseau pour la VEille Spatiale (French Acronym - Large Array for Space Surveillance)
GTO: Geostationary Transfer Orbit
LEO: Low Earth Orbit
MEO: Medium Earth Orbit
R/B: Rocket Body
RCS: Radar Cross Section
S3: Space Surveillance System
VHF: Very High Frequency

2. SPACE SURVEILLANCE SYSTEM ARCHITECTURE

« Space surveillance » is a general term meaning all resources and procedures aimed at procuring the most precise knowledge possible about the 'object population' in orbit around the Earth. It's a well known fact that, since the beginning of the space age, the number of orbiting objects has increased continually.

The need to know the state of this 'space population' is becoming more obvious for all nations involved in space activities.

For these nations, knowledge of the space population is essential in order to be able to:

- Evaluate the status of the space activity worldwide (including military and civilian applications)
- Predict the risk of collision. Several collisions in orbit have already taken place
- Evaluate the encumbrance of « strategic » orbits (geostationary orbits in particular)
- Predict the atmospheric re-entry of objects which may cause damage on the ground.

2.1 Functions of a surveillance system

In order to respond to the issues raised above, a space surveillance system must provide the following capabilities:

- ✓ the detection and subsequent regular monitoring of orbiting objects (orbital parameters),
- ✓ the identification of the origin of these objects (launch site, owner),
- ✓ the provision of a minimum of intelligence on their technical characteristics (size, mass, etc..).

The creation of a database, continually updated with this essential data, would then provide responses to the initial queries of the users of such a system.

The figure below (Fig : 1) illustrates the overall organisation of a space surveillance system. The left-hand part of the diagram deals with the sensors which collect the information, the right-hand part shows the utilisation of this information. The system clearly pivots around a database of this information, especially the satellites' orbital data which constitutes the crucial part of the system because:

- It is essential for the use of tracking and analysis sensors which require precise targeting,
- It forms the basis of the majority of uses relative to the monitoring of activity in space,
- It has to be continually updated taking into account the imperfection of dynamic satellite models as well as the possible occurrence of manoeuvres.

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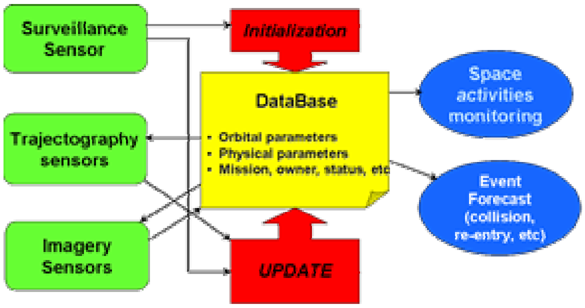

Fig : 1. Organisation of a space activity surveillance system

3. GRAVES SYSTEM SPECIFICATIONS

Intended for military use, the GRAVES system, designed for the DGA (French armament procurement agency), concerns itself with active satellites as a priority. The final specifications for this radar are given below:

- Installation in Metropolitan France
  This specification which simplifies the installation conditions of the sensor has little negative impact on its potential performance taking into account the actual distribution of satellites in orbit

- Detection of all satellites up to an altitude of 1000 km

- Delay in the detection of any satellite less than 24 hours
  This specification arises essentially from the desire of future users of the system to be able to quickly detect new satellites. It also limits the average period between two observations to less than 24 hours.

- Determination of an orbit based on a single pass
  This is a tight constraint since it has an impact on the volume of the surveillance zone. In effect, the determination of an orbit requires a minimum number of measurements, if possible separated in time. This specification would necessitate a « self-sufficient » sensor and the system would no longer rely on a hypothetical tracking radar which would be required to refine the trajectory of the objects detected by the surveillance radar.

4. DESCRIPTION OF THE GRAVES CONCEPT

In order to respect the specifications described above, ONERA's approach has been to propose a simple and inexpensive concept specifically adapted to this mission. Three fundamental questions have to be answered to be able to define a radar surveillance system:

- What is the volume of detection?
- What is the working frequency?
- Nature and quality of the measurements (waveform, signal processing, extracted measurements)?

<u>*Detection volume:*</u>
The choice of the detection volume must be made under two opposing constraints: on the one hand, it is desirable to maximise the volume in order to increase the probability of satellite detection; but at the same time, minimising the emitted power of a system makes its development more feasible. The optimal solution results in a detection volume corresponding to the surface of a cone with a vertical axis. With this set-up, every satellite crosses this « thin envelope » at least in two points. With a three-dimensional measurement vector (angular and range or Doppler measurements), it is then possible to calculate a first orbit for the detected satellite.
For a given envelope, two parameters must be defined:

- The range of the envelope
- The angle of elevation of the envelope

To choose these two parameters, two contradictory constraints need to be taken into account: to minimise the emitted power it is appropriate to observe at a high angle of elevation. However, to be sure of observations at an acceptable frequency, it is advisable to observe at a low elevation (just above the horizon) with, as a consequence, longer observation distances.

A precise analysis has shown that the dimensioning orbits for this choice are geosynchronous (16 , 15 and 14 orbits per day). The analysis of these orbits has resulted in a theoretical concept of 3 envelope radar within which the useable power is distributed according to the table below. A transmission elevation of 11,3° corresponds to the maximal elevation to which the envelope can be oriented to ensure the daily detection of the geosynchronous orbits of 16 passes per day. If a greater elevation is chosen, some orbits may never be detected if they are out of phase.

The advantage of the 3 envelope configuration is to minimise the power emitted compared with that of a one envelope solution. The power emitted has to reach satellites at up to 1000 km in altitude (equivalent to a range of more than 2500 km). If several envelopes are set up, the envelope at 11,3° is only used to detect the orbits of 16 orbits per day and needs a range of only approximately 1000 km. The envelopes at 24,7 and 34,7 degrees are adapted to the orbits of 15 and 14 orbits per day.

	Emission elevation (°)	Range (km)	Maximum altitude (km)	Relative power by envelope (%)
One envelope	11.3	2664	1000	reference
Three envelopes	11.3	1133	315	3.3
	24.7	1194	584	4.2
	34.7	1559	1000	11.6

Fig : 2. Configuration of 1 and 3 envelope radar.

Working Frequency:

The same sort of compromise operates with the choice of frequency. From the point of view of the radar evaluation and of the cost of emitted Kw, the lowest possible frequency would be chosen. On the other hand, in order not to degrade the RCS (Radar cross-section) of the detected objects too much, it is advisable to maintain a wavelength commensurable with the characteristic size of the observed objects. Moreover, the choice of a very low frequency raises the problem, if we wish to maintain an acceptable angular precision, of the influence of the effect of the ionosphere and of the size of the antennas.

In these circumstances and taking account the objective of GRAVES which has to detect satellites and not debris, the VHF wavelength seems to be the optimal choice.

Nature and quality of the measurements:

The GRAVES system being specifically dedicated to space surveillance, it quickly became apparent that it isn't absolutely necessary to be able to measure range and that a measurement of radial velocity (using the Doppler effect), associated with angular measurements is wholly adequate for determining an orbit, provided that two points of measurement are possible. Such a choice is particularly advantageous in terms of the bandwidth required and the waveform since it is possible to transmit a pure frequency. On the other hand, it is necessary to well separate the emission sites and the reception sites to ensure a good decoupling and to avoid saturating the reception stages with the direct path.

The final design for the proposed surveillance radar represents a compromise between:

- On the one hand, the optimal transmission diagram minimising the emitted power to that defined above and,
- On the other hand, the problems of technical feasibility, of ease of implementation and maintenance.

Practically, the generation of a thin envelope requires the implementation of a vertical linear array comprising omni directional elementary azimuth antennas. The choice of the low frequency bandwidth (VHF), for reasons of cost and link budget, would need a mast of more than 30 metres on which would be distributed the elementary antennas.

The compromise which has been worked out involves, covering a « volume » which includes these different envelopes, rather than creating very thin « envelopes » distributed according to the optimal observation elevations.

In order to compensate the increase of power necessary, it has been decided not to install a permanent illumination but, instead, azimuths sweep with a beam which is wide in elevation and relatively narrow in azimuth.

This principle is illustrated in the following figure:

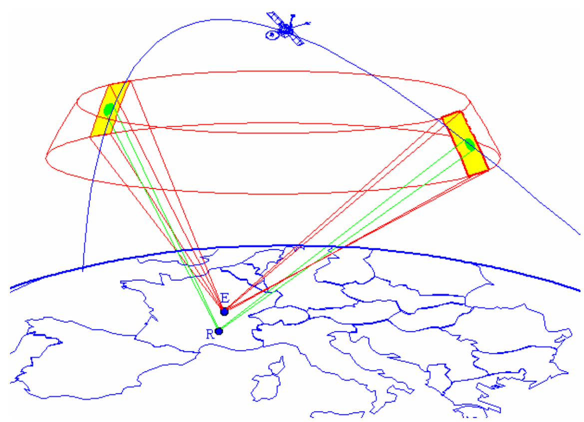

Fig : 3. Illustration of the principle of the GRAVES radar

The GRAVES radar is therefore a continuous emission / Doppler detection radar operating in the VHF bandwidth. The use of continuous emission results in a bistatic radar (transmission and reception at distinct sites).

The transmission is implemented using a phased array and the reception by a technique of digital beam forming.

The system developed by ONERA comprises four panels of transmission antennas, each covering 45° azimuth in approximately 20 seconds with a beam of aperture 8° in azimuth and 20° in elevation. The zone covered extends over 180° azimuth. Strictly, the coverage should be 360 degrees; however, it has been shown in simulation that a coverage 180 degrees azimuth allows the detection of each satellite at least once every 24 hours.

Fig : 4. View of the 4 transmitting antennas

The choice of a frequency in the VHF bandwidth associated with the utilisation of a single frequency has led to the use of transmitters based on a widely available commercial product used in broadcasting. This choice has significantly diminished the cost while benefiting from the reliability of a tried and tested component.

The reception array comprises 100 antennas distributed over a metallic disc forming a ground level surface. Each antenna is linked to an individual receiver whose signals are then digitised. The addition, in phase, of all the signals issuing from the reception antennas results in the creation of a vertical reception beam equivalent to that which would be created by a single antenna of the same size as the disc carrying the antennas (an aperture of the order of 2°).

Fig : 5. Aerial View of the reception site

5. DATA PROCESSING DESCRIPTION

However, we need to be able to observe in all directions illuminated by the transmission. The signals issuing from each antenna being digitised, it is possible to assign to the signal from each antenna a specific phase shift. The choice of an adapted phase set allows the creation of a beam orientated in any direction, not simply the vertical. This technique of digital beam forming (FFC) allows, given a real-time calculator of sufficient power, simultaneous observation in all directions potentially illuminated by the transmission.

Fig : 6. Reception Antennas

The detection of the satellites is then made possible with a Doppler technique by proceeding to the Fourier transformation of the FFC signal.

A preliminary trial model of only two transmission panels was built between 1997 et 2001. The transmission site is situated close to Dijon and the reception site is in Provence. The extension of this system has been ongoing since 2002 and will conclude with the delivery of an operational system to the French Air Force Staff at the end of 2005.

6. CATALOGUE MAINTENANCE PROCESS

As we have just seen, GRAVES relies on a single sensor providing measurements, which precision is necessarily limited since the sensor is a surveillance sensor and not a tracking sensor. Now the objective of this system is to provide a catalogue of orbit parameters for the orbiting objects.

For co-operative satellites, the orbitographical processing which transforms the sensor measurements into orbital parameters is conventional and there is a wide range of processing software. In the context of space surveillance the problems raised are of a different nature:

- The measurements made with the surveillance sensors are not « signed »: we don't know, a priori, which tracks of obtained measurements belong to which satellite,

- The volume of data to process is considerable and requires the use of rapid orbital models (analytical or analytical-numerical) with a precision which is necessarily limited,
- The measurements obtained during the first pass of a satellite are very un-accurate and result in a first orbit determination of very poor quality. This situation highlights the difficulties linked to the non-linearity inherent in any orbit estimation. This problem is made even more difficult by the absence of any measurement of distance, as in the case of GRAVES.
- The observation frequency of the satellites is necessarily limited taking into account the performance of surveillance sensors and the recognition of a satellite during its successive passes is especially tricky.

In summary, the most important problem in the creation of a database of orbital data is to collect together all the successive tracks of measurements for the same satellite. Once this has been achieved, we may simply use the « classical » orbit determination techniques. To give an idea of the task to accomplish, 10 days of GRAVES sensor data results in more than 1.700.000 measurements distributed over more than 55.000 tracks, which must all be processed.

Four modules (one optional) carry out the orbitographical processing:

Short term tracking: This module is designed to group together on the same track all the measurements carried out for the same satellite during one of its visible passes. Taking into account the short duration, a keplerian orbital model is used. The technique involves the collection of measurements with which a viable orbit may be aligned.

Long term tracking: This module is designed to group together the tracks, output by the module described above, for the same satellite. A technique equivalent to the short term tracking is used but, the interval between two tracks being of the order of a day; a more precise analytical orbital model is used.

Final tracking: Long term tracking is appropriate when the satellites are in a natural orbital movement. However, if manoeuvres take place, this module can only associate the tracks obtained before and after the manoeuvre. In this case, long term tracking gives rise to the creation of a new object; the catalogue remains coherent but the identity of the manoeuvring satellite is lost. The objective of final tracking is to deal with this problem. It permits the correlation of orbits which may be linked by posing the hypothesis of an orbital manoeuvre of reasonable amplitude.

External identification (optional module): the processing of GRAVES is designed to function autonomously (without external information). However, it was judged useful to be able to compare the orbits obtained by GRAVES with those issued by the US Space Command in the form of Two-Lines data. The external identification module allows this correlation to be made.

7. SOME RESULTS

GRAVES has already been the subject of several experimental programmes which have verified its potentialities in terms of:

- Population of detected satellites
- Capability of creating ex-nihilo a catalogue of detected objects

Detected objects:
The figures presented below are the outcome of experiment carried out at the end of 2004. During this period, based on the identifications compared with the data of the US Space Command, more than 2300 different objects could be observed.

In this population, only a small proportion of debris is detected. This result is coherent with the specifications for GRAVES which aims at the detection of satellites. The choice of a working frequency in the VHF bandwidth proves to be unsuitable for the detection of objects whose characteristic size is much lower than the wavelength.

The figure below presents the distribution of the satellites detected. The altitudes of apogee and of perigee are plotted as a function of the inclination of orbit.

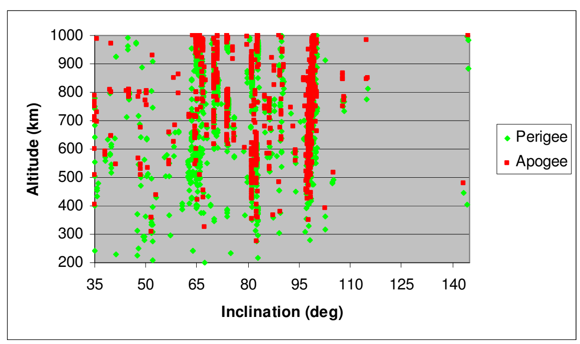

Fig : 7. Orbital distribution of the detected objects

Creation of a catalogue of detected orbits:
The orbital processing modules described in paragraph 6 have been tested during this programme of measurements in real conditions. That is to say, in making the hypothesis of a catalogue which is initially empty and building and refining it according to the observations of the satellites.
The utilisation of the three tracking modules described in paragraph 4 has resulted in the creation of a catalogue of

the detected objects for which the detection frequency was high enough. For the objects which figure in the database published by the US Space Command, the coherence between the orbits recorded in the two catalogues has been successfully verified.

The fine adjustments to the algorithms as well as the evaluation of the final performance will require, of course, new programmes of measurements and the objective is to carry out, in the very short term, a programme of at least one month in order to have available an adequate test database. This programme will allow, moreover, the validation of the complete radar system.

8. CONCLUSION AND PERSPECTIVES

GRAVES is an original space surveillance system which has been specifically developed for this mission. It has been successfully tested during several different experimental programmes. A particular effort has been made to ensure, on the basis of the trial model developed between 1997 and 2000, the construction of an operational system which may be used by the French Air Force. With this aim in mind, work has been carried out to enhance its reliability as well as its extensibility. The latter allows remote operation, without any human presence at the transmission and reception sites. Similarly, the orbitographical processing software has been designed to minimise human intervention.

As a result, the system is now ready to be delivered to the French Air Force Staff at the end of 2005 thus equipping France with a first capability in space surveillance.

As has been indicated at the beginning of this article, a surveillance system constitutes only the first stone in the construction of a system of space surveillance. Following this commissioning of GRAVES, the accent will be now be put on the development of sensors and tools which will be used « upstream» of GRAVES for, in particular, the task of identification. ONERA is well placed to take part in these developments bearing in mind the capacities already demonstrated in the field of ISAR radar imaging and of high resolution optical imaging. It should also be remembered that ONERA is the prime contractor of the NAOS adaptive optics system installed on the ESO telescopes in Chile.

Moreover, the experience acquired by ONERA during the development of GRAVES positions it as an essential player in the development of a future European space surveillance system. ONERA is also leading, for the European Space Agency, the feasibility study of such a system which is the subject of an invited presentation, as part of this conference.

9. ACKNOWLEDGEMENTS

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