PROJECT: SPACE DEBRIS DETECTION AND MONITORING FEASIBILITY STUDY FOR LOW COST PROGRAM

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Contents

1. Introduction

1.1 Scope

The overall scope of this document is to summarise the results of the *Space Debris Detection and Monitoring Feasibility Study for Low Cost Program* documented in the Final Report [A2]. This Feasibility Study provides the background and the first performance estimation related to the possible future development of an European Space Debris Detection and Monitoring System on the basis of a ground-based and a space-based independent sub-system.

1.2 Acronyms

ASI	Agenzia Spaziale Italiana
BITE	Built-In Test Equipment
DISCOS	Database and Information System Characterising Objects in Space
ECM	Electronic Counter Measure
EIKA	Extended Interaction Klystron Amplifier
EIKO	Extended Interaction Klystron Oscillator
EIK	Extended Interaction Klystron
EIRP	Effective Isotropic Radiated Power
ESA	European Space Agency
ESOC	European Space Operations Centre
EURECA	EUropean REtrievable CArrier
FFT	Fast Fourier Transform
FGAN	Forschungsgesellschaft für Angewandte Naturwissenschaften e.V.
FM	Frequency Modulation
GEO	Geostationary Orbit
HW	HardWare
IF	Intermediate Frequency
INS	InterSpace
ISS	International Space Station
ITALSAT	ITALian SATellite
LEO	Low Earth Orbit
MASTER	Meteoroid And Space debris Terrestrial Environment Reference
MMIC	Monolithic Microwave Integrated Circuit
NASA	National Aeronautics and Space Administration
OCI	Oerlikon Contraves Italia
PRF	Pulse Repetition Frequency
PRT	Pulse Repetition Time
RA	Radio-Astronomy
RF	Radio-Frequency
rms	root mean squared
RX	receiving

STS	Shuttle Transportation System
TLC	Telecommunication
TPZ	Telespazio
TX	transmitting
TT&C	Telemetry, Tracking and Command
USR	Università degli Studi di Roma “La Sapienza”
VLBI	Very Long Baseline Interferometry

1.3 Applicable and Reference Documents

1.3.1 Applicable Documents

A1. “*Space Debris Detection and Monitoring Feasibility Study for Low Cost Program*”, Telespazio Proposal - Proposal No: S016/SSS/PRO/001, Issue 1, 21/07/98;
A2. “*Space Debris Detection and Monitoring Feasibility Study for Low Cost Program*”, Final Report, Doc.No. 190.210-CCD-RE-001, Issue 1.0, Date 02.02.1999.

1.3.2 Reference Documents

R1. Editor in Chief, M.I.Skolnik “*Radar Handbook*”, Second Edition, McGraw-Hill, Inc., 1990
R2. M.I. Skolnik “*Introduction to Radar Systems”*, McGraw-Hill, 1981
R3. F.E. Nathanson, ”*Radar Design Principles*”, McGraw Hill, 1969
R4. D.K.Barton, “*Modern Radar System Analysis*”, Artech House, 1988
R5. B.Pavesi, G.Rondinelli, C.Buongiorno, F.Graziani, G.B.Palmerini, F.Santoni and I.Bekey, “*Innovative Techniques for Small Space Debris Detection*”, 49th International Astronautical Congress, Sept 28- Oct 2, 1998 / Melbourne, Australia;

1.4 Summary

The Space Debris Detection and Monitoring Feasibility Study for Low Cost Program is a feasibility study performed to provide a relevant service definition and a technical assessment about the performance of a Ground-to-ground Bistatic System and a Space-based Monostatic Radar.

This feasibility study is focused on a space debris environment monitoring:

- to acquire a better technical knowledge of space debris environment around the Earth below 1000 km of altitude - it will be possible to extend the technical evaluations out of this range, up to 2000 kilometres of altitude - for space debris diameters between 0.5 and 50 cm;
- to assure a timely protection of manned spacecraft like the ISS for avoiding dangerous impacts (for space debris diameters greater than 1 cm).

More in detail, in addition to a technical assessment of the systems performance, the study provides a potential user requirement analysis, hypothesis about some architectural solutions and a data processing and handling definition for both systems, also.

The study is completed by a description of the relevant international scenario and commercial aspects.

Finally, chapter 5 briefly describes the possible future steps to realise the aforementioned European System.

2. Service Definition

2.1 Requirements analysis

The main general requirements are the following:

- validation of space debris models (e.g. MASTER) by observing the space debris environment on a regular basis;
- improve accuracy of orbital elements for objects that come close to a valuable space asset;
- get information on special objects to verify the physical status (intact or fragmented);
- debris size of major interest is between 0.5 and 50 cm for the maintenance and the integration of a space debris database (i.e.: ESOC's DISCOS);
- manned spacecraft (ISS, Space Shuttle, ...) safety general requirements (collision avoidance).

It is possible to satisfy these requirements by means of the Ground-to-ground Bistatic System and the Space-based Monostatic Radar which will be briefly described in the following chapters 3 and 4.

2.2 Data Management, Processing and Handling

With the expression "data management" we refer to how we intend to manage the raw, the processed (output of "data processing") and the elaborated (output of "data handling") data inside the proposed systems.
The aim of this management is to distribute on a suitable design to perform the processing and handling of the raw-data and to maintain and to integrate suitable databases as ESOC's DISCOS.

The "data processing" is the elaboration of the echo radar signal reflected after to be analogic-to-digital converted.
The main functions accomplished by the data processing are threshold estimation and debris detection, range estimation, angular errors estimation, position calculation, velocity vector calculation and trajectory estimation.

With the expression "data handling" we refer to how we intend to use the data processed by the signal analysis algorithms: the output of this processing (to say the input for "data handling") are the radar cross section and the state vector (position and velocity) evaluation of the detected debris.
A key point of this feasibility study is investigating the possibility to achieve an estimate of the debris orbital elements.
Of course, this estimate may be more or less accurate depending on the measurement errors: then, we analysed in detail the effects of different kind of measurement errors on the orbital elements evaluation.

3. Ground-to-ground Bistatic System

3.1 Facilities survey and technical aspects

In order to satisfy the main requirements of this feasibility study (low cost, easy to be implemented and short time availability [A1]), an accurate TX and RX antenna facilities survey has been performed. This survey has allowed the system designer to evaluate all relevant technical characteristics and all relevant availability information.
All TPZ's space centres (or managed by TPZ) on Italy's territory (*Fucino*, *Lario*, *Matera*, *Scanzano* and *Spino d'Adda*) and nine ITALSAT TX/RX fixed and transportable antenna facilities have been involved in the survey; up to 119 antenna's facilities have been evaluated.
It is important to note that the utilisation of a RX site at a low latitude (with respect to european latitude), allows the system to provide information relevant to space debris orbiting with a low inclination angles, also. As a matter of fact, for non-equatorial TX and RX sites, the lower limit of the space debris inclination angle for investigating relevant information is fixed by the maximum two-ways range that allows the system to provide utilisable results.

In order to provide some reasonable hypothesis about the *Concept Test* and the *Final System* architectures, the designer analysed some technical aspects. The most important of this technical assessment is briefly described below.
The existing TLC up-link signals towards GEO satellites are basically digital QPSK modulated. To detect debris by using a dedicated receiving ground station it is necessary to correlate the received digital signal with a copy of the transmitted one.
Unfortunately, the unknown Doppler frequency shift caused by the debris unknown speed, that in this case with 30 GHz as carrier frequency ($\lambda = 1$ cm), could reach 400 KHz ($v_{radial} = 2$ km/s), does not allow a perfect coherent demodulation.
To reduce this negative effect, a large number of filters, each one centred for each expected Doppler frequency shift should be necessary. This in other words means to implement an FFT processing with a large number of points which results unfeasible for real-time application.
On the other hand, by implementing a feasible FFT processing, the residual Doppler frequency destroys the phase information of the transmitted signal and for this reason it is not convenient to use the QPSK digital signal available from the existing TLC stations.
This does not mean that the existing TLC station will not be used, but more precisely, that it is necessary to transmit a dedicated QPSK digital signal, that is, an opportune phase coded waveform capable to mitigate this kind of unknown Doppler frequency shift problem.

3.2 Signal Design

Even though the doppler frequency displacement expected is quite large, about _400 kHz, it is very important to insert an opportune phase coding in order to improve the range resolution by auto-correlation in the receiving side and, at the same time, to maximise the transmitted energy.

For this application, a classical pseudo-random Biphase coded sequence [R1] is suitable. In order to have the maximum unambiguous range greater than 2000 km, and simultaneously a reasonable resolution of 150 m (1 _s), it is necessary to implement a 14 stages shift-register code generator to have a 16383 code length. The clock rate of the above shift register generator is 1 MHz in order to achieve 1 _s as resulting range bin.

This solution results completely suitable to be integrated with the existing transmitter stations, but the frequency resolution in the FFT filtering produces a Doppler frequency residual at the output, before the pulse compression. To reject this effect, it is necessary to have an FFT with a large number of points by adding zeroes to the received samples. Therefore an on-line processing is not suitable with this solution, which remains valid if an off-line processing is allowed.

To overcome this problem [R3], a more appropriate linear FM compression technique could be adopted, but this kind of pulse compression seems unfortunately not to be compatible with the available transmitters, unless modifications are carried out.

A feasible solution is then to use a Frank polyphase code, which, although with less performance than the linear FM compression, constitutes a good approximation of it, that can be easily implemented without requiring hardware changes to the available transmitters (low cost requirement) [R4].

The receiver on the ground receiving station is then based on a completely coherent receiving chain.

The complete pre-processing presents anyway some losses that should be inserted in the radar equation to evaluate the range performance. Considering the complexity of the pre-processor, to assume at least 5 dB total pre-processing losses seems to be reasonable.

3.3 Ground-to-ground Concept Test: definition and results

In the case of ground-based systems, it is possible to perform a *Concept Test* to verify the feasibility of the space debris detection and monitoring system.

In order to perform this Concept Test taking into account the low cost requirement, it is possible to use a RX antenna facility installed at the Spino d’Adda Space Centre (diameter equal to 3.5 m), while for what concerns the TX antenna facility there are two alternatives.

The first TX alternative provides for the utilisation of an ITALSAT transportable antenna facility; this kind of antenna facility (equivalent diameter equal to 2.7 m) can provide an EIRP equal to 73 dBw.

The second TX alternative provides for the utilisation of the ITALSAT antenna facility located at Avigliana (near Torino); this kind of antenna facility (equivalent diameter equal to 5.2 m) can provide an EIRP equal to 78 dBw.

In both TX alternatives, using a Ka-band frequency (ITALSAT frequency, near to 30 GHz), with an atmospheric attenuation value equal to 0.21 dB and a narrow-baseband (10 Hz) signal, by means of application an algorithm based on the radar equation (assuming the receiving system temperature equal to 140 K, the portion of impinging power reflected towards the receiver by the debris equal to 0.3, the atmospheric attenuation equal to 0.21 dB and the RX simple space debris detection (S/N = 3 dB) and complete space debris detection (S/N = 10 dB) cases [R5]:

with an ITALSAT transportable antenna facility (EIRP Arx = 80 dBw m^2):

TX-space debris-RX half-path [km]	space debris diameter [cm] (S/N = 3 dB)	space debris diameter [cm] (S/N = 10 dB *)
500	13.3	29.7
750	24.4	54.6
1000	37.6	84.1
1500	69.0	> 100
2000	> 100	> 100

*: Probability of detection equal to 30%.

with the ITALSAT antenna facility located at Avigliana (Torino), (EIRP Arx = 85 dBw m^2); baseline *Avigliana - Spino d'Adda* ≈ 168 km:

TX-space debris-RX half-path [km]	maximum altitude inspectable [km]	space debris diameter [cm] (S/N = 3 dB)	space debris diameter [cm] (S/N = 10 dB *)
500	493	7.5	16.7
750	745	13.7	30.7
1000	996	21.1	47.3
1500	1498	38.8	86.8
2000	1998	59.8	> 100

*: Probability of detection equal to 30%.

It is important to note that for what concerns the data relevant S/N = 10 dB, the probability of detection equal to 30% is a very good value considering that the proposed systems could provide a continuous service.

The Concept Test should be realised on the basis of space debris crossing input data provided by ESOC by means of stored data in DISCOS.
In this way, a timely planning of observation and measurement campaigns, will allow a minimum duration of experiment because these campaigns will be related to periods of time needed to detect some crossing of big catalogued space debris, only.

3.4 Ground-to-ground Bistatic System: definition and results

For what concerns the Ground-to-ground Bistatic System, the better solutions are shown in the following table:

	TX antenna facilities	RX antenna facilities
1	*Bari* - ITALSAT Traffic (managed by TPZ)	*Matera* - VLBI (RA) (ASI - managed by TPZ)
2	Spino d'Adda - ITALSAT Traffic Prototype (managed by TPZ)	*Matera* - VLBI (RA) (ASI - managed by TPZ)

The first alternative - Bari (as TX) - Matera (as RX):

For what concerns the TX antenna facility, located at Bari, it is possible to use an ITALSAT Traffic Antenna Facility (equivalent diameter equal to 5,5 m) providing an EIRP equal to 78 dBw. For what concerns the RX antenna facility, located at Matera Space Centre, it is possible to use a VLBI Station (diameter equal to 20 m).

Currently, the RX antenna feed receives the signals in S-Band (2,210*2,450 MHz) and in X-Band (8,180*8,980 MHz), but it is reasonable to use the same antenna in Ka-Band (ITALSAT frequency) because the panels forming the antenna's surface have a good alignment (order of magnitude of rms equal to few millimetres) with respect to the relevant wavelength (near to 1 cm).

Starting from this operative situation, it will be needed to integrate this antenna facility with a new monopulse feed working at 30 GHz; for what concerns the RF → IF chain, it will be possible to use existing HW used to perform the Concept Test (low cost requirement).

With this system configuration, with the same condition and algorithm of the Concept Test, it is possible to obtain the following results in both simple space debris detection (S/N = 3 dB) and complete space debris detection (S/N = 10 dB) cases [R5]:

(EIRP Arx = 100 dBw m^2); baseline *Bari* - *Matera* ≈ 55 km:

TX-space debris-RX half-path [km]	maximum altitude inspectable [km]	space debris diameter [cm] (S/N = 3 dB)	space debris diameter [cm] (S/N = 10 dB *)
500	499	1.3	3.0
750	749	2.4	5.4
1000	1000	3.8	8.4
1500	1500	6.9	15.4
2000	2000	10.6	23.8

*: Probability of detection equal to 30%.

It is important to note that for what concerns the data relevant S/N = 10 dB, the probability of detection equal to 30% is a very good value considering that the proposed systems could provide a continuous service.

The second alternative - Spino d'Adda (as TX) - Matera (as RX):

For what concerns the TX antenna facility, located at Spino d'Adda Space Centre, it is possible to use a prototype of an ITALSAT Traffic Station (diameter equal to 5 m) providing an EIRP equal to 80 dBw. For what concerns the RX antenna facility, see the first alternative.

With this system configuration, with the same condition and algorithm of the Concept Test, it is possible to obtain the following results in both simple space debris detection (S/N = 3 dB) and complete space debris detection (S/N = 10 dB) cases [R5]:

(EIRP Arx = 102 dBw m^2); baseline *Spino d'Adda - Matera* ≈ 790 km:

TX-space debris-RX half-path [km]	maximum altitude inspectable [km]	space debris diameter [cm] (S/N = 3 dB)	space debris diameter [cm] (S/N = 10 dB *)
500	307	1.1	2.4
750	638	1.9	4.3
1000	919	3.0	6.7
1500	1447	5.5	12.3
2000	1961	8.4	18.9

*: Probability of detection equal to 30%.

It is important to note that for what concerns the data relevant S/N = 10 dB, the probability of detection equal to 30% is a very good value considering that the proposed systems could provide a continuous service.

3.5 Orbital elements evaluation: effects of measurement errors

One goal of this feasibility study is investigating the possibility to achieve an estimate of the debris orbital elements. The proposed system provides an estimate of the position and the velocity (state vector) of the detected debris; from the position and the velocity we are able to calculate the orbital elements. As the measures are affected by inaccuracies, we have examined how these inaccuracies may affect the orbital elements calculation.

The output of the data processing are the position and velocity evaluated in a point of the debris orbit; more in detail the output provided are:

- the range (*R*) information which comes up from the time distance from the transmitter to the debris (R_t) and from the latter to the receiver (R_r): $R = \frac{R_t + R_r}{2}$; of course, in the bistatic case, from the angular position of the target with respect to the transmitter and the receiver, we can evaluate the range without using the time distance information; however, as the angular positions measures are affected by errors, the range estimate provided by the time distance can be rather useful;
- the angular position and velocity, i.e. the elevation and azimuth angles relative to the receiver (El_r, Az_r) and their respective time derivatives ($\dot{El}_r$, $\dot{Az}_r$); the angular measurement are a direct output of the system, while the time derivatives are achieved through the angular position signal evolution during the dwell time;
- the doppler frequency doesn't provide the range rate, but rather the velocity component in the direction of the bisector of the angle $T_x\hat{D}R_x$ (called β in the Fig.3.5-A).

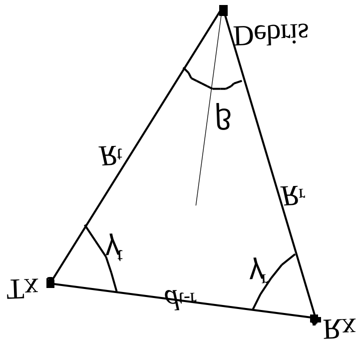

Fig.3.5-A: Transmitter-debris-receiver plane

Some mathematics is needed to manipulate the processed data as to achieve the state vector in a suitable reference frame; from this vector we can get the orbital elements and we can evaluate the effects of the measurement errors. In this study we have evaluated these effects by means of a simulating software; we have taken into account inaccuracies having the following order of magnitude:

- 10 km or less for the range;
- 0.05° or less for the angular measures and 0.1 deg/sec or less for the angular rate estimates; note that as the angular derivatives are not directly measured, their evaluation precision is limited by the relative angular measurement accuracy and by the dwell time;
- 1 km/s or less for the doppler frequency velocity component; we point out that 1 km/s is the order of magnitude of the doppler frequency velocity component itself.

It is useful to say how “small” or “great” the errors are with respect to realistic measures. As far as the range is concerned, we can say that the distance resolution is of the order of 100-150 m, so that the inaccuracy can not be smaller than this value. With regard to the doppler velocity, we can expect to have errors as small as 20-30 m/s. Concerning the angular inaccuracies the problem, as we stated above, is the tangent velocity evaluation which is carried out from the evolution of the angular position signal during the dwell time; we can say that the angular accuracy, for a monopulse receiver, is of the order of one hundredth of the beam, which in turn could be about 0.2°; the angular velocity error can be roughly carried out as twice the angular error divided by the dwell time.

In the Fig.s 3.5-B and 3.5-C, are presented diagrams showing the variation of the semi-major axis error as a function of the different possible kinds of errors: each plot is obtained keeping all the errors constant to “small” values (in the sense hereafter explained) except one inaccuracy which vary. Of course when varying the angular error also the respective time derivative changes. With the adjective “small” we indicate inaccuracies such that both the orbital plane (inclination and right ascension of the ascending node) and the orbit geometry (semi-major axis and eccentricity) are satisfactorily evaluated; the order of magnitude of such errors are: range error 0.1 km, angular errors 0.0005°, doppler frequency velocity component error 0.01 km/s, angular rates errors 0.001 deg/s.

We point out that in Fig.3.5-B the receiver elevation and azimuth errors are respectively $R \sin \Delta El_r$ and $R \sin \Delta Az_r$.

The following are the results of our analysis:

- the orbital plane can be determined with satisfactory accuracy so that we can update debris models with respect to inclination distribution;
- the orbit geometry is critical (but not impossible) to acquire; in the worst case we can use position estimates to improve the statistics about debris altitude distribution;
- the in-plane orbit orientation is difficult to achieve (especially for almost circular orbits); however the debris distribution in argument of periapsis is quite uniform due to perturbations.

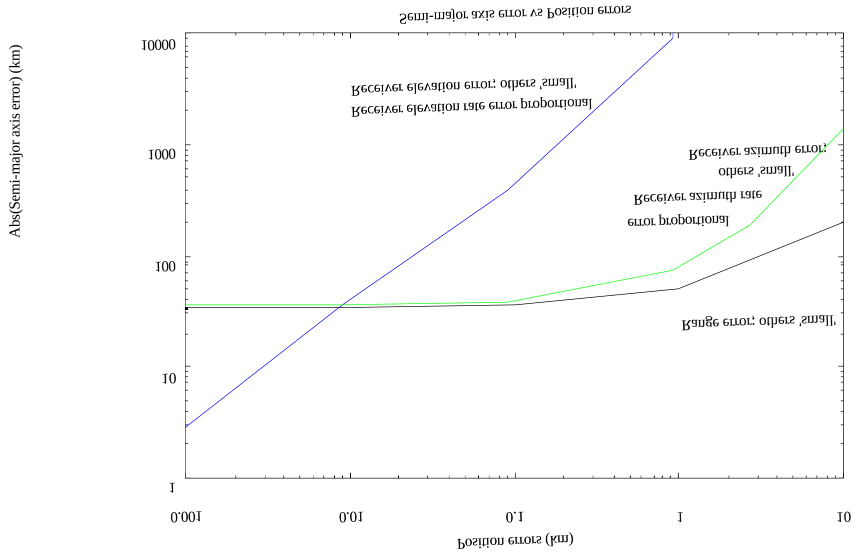

Fig.3.5-B: Semi-major axis error vs position errors

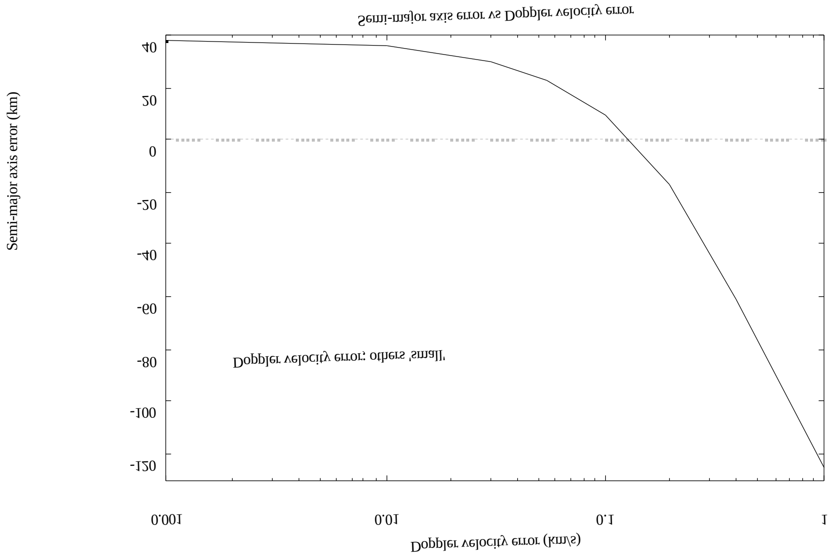

Fig.3.5-C: Semi-major axis error vs doppler velocity error

4. Space-based Monostatic Radar

4.1 The 95 GHz Radar and technical aspects for space application

The 95 GHz radar derives from previous team experience in both the military (tracking radar) and civil (airport surveillance radar for surface movements and guidance control systems) fields of application.

The tracking radar subsystem is a coherent-on-transmit monopulse radar operating in the W-band. Its main technical characteristics are as follows:

- W-band operation to achieve the following advantages:
  Small beamwidth for multipath free operation;
  Very high degree of resolution and accuracy;
  High ECM immunity.
- Monopulse Cassegrain antenna with azimuth micro-scan capability;
- Coherent on transmit operation using an injection locked Extended Interaction Klystron Oscillator (EIKO);
- Automatic frequency control;
- Monopulse receiver;
- Moving Target Detector by FFT Doppler filtering;
- Algorithms and automatic procedures to optimise the performance with regard to the environment;
- Early-Late gate range error extractor;
- Electronic range axis;
- Digital vector angular error extractor;
- Automatic calibration;
- Fault detection and isolation;
- Subsystem management and interfacing controlled by microprocessor.

The radar is very small and compact. As a matter of fact, the maximum weight of the antenna unit is less than 50 kg, the maximum weight of the electronics cabinet is less than 35 kg, and the overall dimensions of the antenna unit are: 500 mm height, 500 mm width, 845 mm depth, while the overall dimensions of the electronics cabinet are: 445 mm height, 530 mm width, 240 mm depth.

To use the millimetre wave radar in a spatial environment, the main factors to be taken into account are - together with reliability - volume and weight of the waveguide parts, as they are used in the existing ground-based millimetre wave radar.

To improve interface effectiveness with the horns, a suitable choice is the use of in-wave components: moreover the effort to achieve reduced volume and weight, by using less components, will lead to a reliability increase too: this objective could be achieved by using a MMIC in the conversion section instead of an in-wave mixer. It should be anyway considered that this solution requires a bigger economic effort, mainly in the design and development

MMIC technology is used also for the other radar assemblies, in particular for the microwave section of the local oscillator, the integration advantages become still more emphasised.

As far as the millimetre wave radar parts devoted to the receiving and frequency conversion functions are concerned, which include the millimetre band low-noise amplifier, the most relevant technological aspect is by far the amplifier and converter section, which directly affects the radar sensitivity performance. This section asks for extremely advanced technological solutions, specially for the low-noise amplifier; in particular the critical items are represented by the development of active devices of p-hemt type, with channel dimension very small and a gate of about 0.1÷0.15 μs: presently very few suppliers are able to develop and manufacture components with such characteristics.

The noise figure of the device and the conversion loss of the guide transition - which cannot be avoided - are the limiting factors of radar performance.

As regards the realisation of the millimetre band transmitter, the main points to be considered in the use of an EIK tube are highlighted here: first of all, the use of the tube for spatial applications has to be faced together with the manufacturer, mainly for the aspects of validation/changes of high voltage insulation, and for tube qualification; then the power supply shall be redesigned to meet spatial environment requirements. The main activities are the choice of the most suitable high voltage insulation technique, the design review finalised to achieve the reliability requirements, the search for the power components able to satisfy the parts selection criteria, the changes in the protection and test philosophy to adapt it to a different BITE concept.

4.2 Signal Design and Space-based Monostatic Radar: definition and results

The Space-based Monostatic Radar is a millimetre wave sensor working at 95 GHz. The sensor uses a monopulse Cassegrain antenna in order to extract further information about the debris trajectory when it passes through the antenna beam. The antenna has 1 m diameter with 0.2° beamwidth and 59.6 dB gain.

The transmitter is based on EIKA (Extended Interaction Klystron Amplifier) tube amplifier which is capable to provide up to 1200 W peak power with 10% duty cycle and 850 MHz bandwidth (at _ 1 dB).

The energy is radiated by means of two coded waveforms; the shorter one is a train of four 1 _s 13-Barker [R2] coded pulses and the longer one is 40 _s 121-element Frank-coded waveform [R2].

The pulse codification has been necessary in order to improve the range resolution and simultaneously to optimise the range coverage by maximising the transmitted energy.

In this application the "time on target" is strongly dependent on both radial position (distance from the sensor) and debris velocity that is assumed to be located between 5km/s and 15 km/s.

Considering the 10% which maximum duty cycle available from the tube amplifier (EIKA), by using the longer pulse, 40 _s, the maximum PRF value usable is 2500 Hz, that is 400 _s as pulse repetition time (PRT).

The 2500 Hz PRF value corresponds to have 60 km as maximum unambiguous range. Due to the fact that for debris having a 50 cm diameter, the range performance results greater than 60 km, it has been necessary to increase the unambiguous range by using four different transmitting frequencies.

These frequencies, F1_F4, need to be separated by twice maximum doppler frequency expected, that is, 32 MHz, which corresponds to consider _24 km/s as maximum radial velocity expected from debris without any ambiguity in range measurement.

In this way, the overall transmitted band results 128 MHz, with 327 km as overall maximum unambiguous range covered.

During the transmission of the 40 _s long pulse at frequency F1, the receiver front-end will result protected giving rise to a near blind zone of about 6 km radius. It is very important to underline that if the near zone (up to 6 km) is not significant for the debris detection point of view, it is then possible to eliminate the train of four short pulse in order to simplify the transceiver.

In order to detect debris inside this zone, it is necessary to transmit between this long pulse and the following one, a shorter pulse.

Therefore, to compensate the further reduction of the observation time at shorter range, it results more convenient to transmit a train of four short pulse, each one 1 _s length at 10 _s time rate, in order to increase in such way the number of available echo returns in the "time on target".

In addition, to detect debris inside the other three blind zones caused by the protection of the receiver during the transmission of the pulses at frequency F2, F3 and F4, four different PRT must be implemented.

The timing for the transmission must be chosen in order to make sure that only one detection can be missed during the observation time. The values chosen are listed in the following table:

Sequence Number	**T_{1i} (_s); $i=1,2,3,4$**	**T_2 (_s)**
1 (F1)	45	400
2 (F2)	85 (45+40)	400
3 (F3)	125 (45+2*40)	400
4 (F4)	165 (45+3*40)	400

The PRT values are to be changed according to the frequency planned.

The radar receiver is based on a completely coherent receiving chain.

The main parameters of the sensor are summarised in the following table:

Parameters	**Unit**
Peak Transmitted Power	1200 W
Transmitting Loss	1.5 dB
Receiving Loss	1.5 dB
Noise Figure	4.5 dB
Pulses length	1 s, 40 s

Antenna Diameter (Cassegrain Monopulse)	1 m
Mismatching Loss	1 dB
Beam shaping Loss	1.6 dB
PRF (staggered)	2.5 _ 100 kHz
A/D conversion Loss	0.8 dB

In the following table the range performance has been summarised for two particular 90% and 50% detection probability. The evaluation has been performed considering 10^{-6} as probability of false alarm (pfa) and the debris object like a Swerling 1 fluctuating target, transmitted pulse 40 _s.

	Range (km)								
Pd (%)	**1 cm Debris**			**10 cm Debris**			**50 cm Debris**		
	5 km/s	10 km/s	15 km/s	5 km/s	10 km/s	15 km/s	5 km/s	10 km/s	15 km/s
90	16.5	12.7	10	76.6	60.7	54	223	176.4	154.8
50	22.7	17.4	15.8	104.6	82.5	72.6	304.7	242.7	211.7

The Fig.4.2-A shows angle and range tracking accuracy respectively, for a debris having 10 cm diameter:

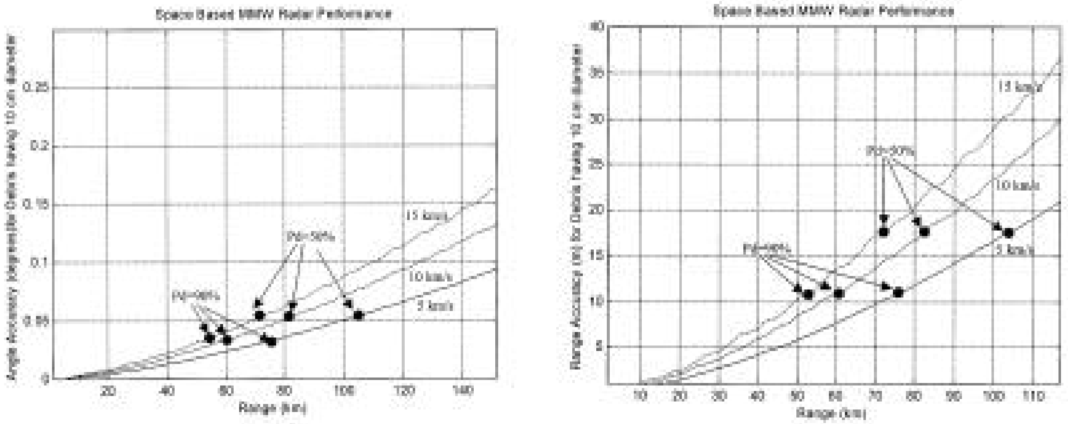

Fig.4.2-A - Angle and range accuracy for debris having 10 cm diameter

For what concerns the effects of measurement errors on the orbital elements evaluation, see paragraph 3.5.

4.3 Application on a free-flier

It would be very satisfactory having a satellite capable to scan every debris crowded region around the Earth; this is not possible because of the limited range of any kind of sensor: if we put the satellite into an orbit with high eccentricity, we wouldn't achieve significant data, from a statistical standpoint, about debris in any altitude region. Consequently, we have to limit the height range scanned by the spacecraft.

If our aim is scanning the most crowded altitudes and inclination regions, the orbit average height could be chosen around 1000 km (debris flux characterised by a maximum). As the greatest part of the LEO debris have inclinations between 60 and 110 degrees, an inclination chosen in this interval seems to be suitable as it allows encounters characterised by smaller relative velocities (allowing easier radar detections). On the other hand we would like to have an inclination such that it is possible to use the J_2 secular effects on the right ascension of the ascending node and on the argument of periapsis to examine ever-different regions; from this point of view we can say:

- with $i = 0°$ we have a relative maximum in the rotation of the line of apsides; as for an equatorial orbit the nodal line is not defined, the effect of the "precession" is a further rotation of the line of apsides: in the present case the overall line of apsides rotation is about 6 deg/day. With this orbit it is not possible to scan a spherical region around the Earth: the debris would be detected when crossing the equatorial plane;
- as we are not interested in the precession of the orbital plane, but rather in the difference between the "Free Flier" orbit precession and the debris ones, we could use a 90° inclined orbit, which implies a relatively fast rotation of the apsidal line, a favourable inclination with respect to the debris ones, and a simple orbit insertion from whichever latitude launch site; the precession of the debris orbital planes would provide encounters with fragments orbiting on different planes;
- with $i = 180°$ the overall rotation is about 18 deg/day. However this kind of orbit would be more expensive to reach.

In conclusion we can say that, if we want to maximise the rotation of the line of apsides, it is convenient to use a 0° orbit inclination; otherwise a polar orbit looks interesting.

We have now to design the eccentricity: as we have said, the height interval should be compatible with the necessity to get significant statistical data: we suppose that the ratio between the volume scanned by the sensor and the total volume between the perigee and apogee altitudes is a significant parameter for statistic purposes; as a result, if only one sensor is employed and the target size is 5 cm, less than 6 years are needed to examine a 3% sample (which can be considered significant) of the region between 900 and 1100 km of height. Of course the radar range is a function of the target dimension, so that for a debris greater than 5 cm the things go even better.

If we are interested in acquiring information about the environment where a certain manned spacecraft or station is orbiting, the free flier orbit inclination should be the same as the cited spacecraft and the perigee and apogee altitudes should be respectively lower and greater with respect to the one of the manned satellite.

5. Future steps

This feasibility study for space debris detection has been performed with a low-cost concept as driver. In other words, this means to design the described technical solutions starting from existing TX / RX facilities. The project requirements have allowed to obtain architectural solutions characterised by very low cost to implement and operate the requested systems with good results. The study shows that in Europe an effort at low-cost can be undertaken to realise space debris detection and monitoring systems in order to perform very useful observations of the space debris environment. Thus Europe could substantially contribute to space debris observation which is until today mainly done by the USA and Russia.

This feasibility study describes the steps to realise ground-to-ground and space-based architectural solutions.

5.1 Ground-to-ground Bistatic System

For what concerns the ground-to-ground architectural line, the second step - after this theoretical phase - should be the experimental phase: the *Concept Test* (see par.3.3). In this phase, the proposed solution consisting of the quasi-ready TX and RX sub-systems will be used to perform the necessary tests to confirm the expected results. The goal of the experimental phase should be a field test with existing facilities and hardware and the tuning of the acquisition, data-processing and data-handling chains.

The detection and monitoring of centimeter-sized space debris on a regular basis should be the goal of the third phase - the operational phase - when the *Final System* shall be in place (see par.3.4). Also in this phase, the low cost driver should guide the designer to reuse the acquisition, the data-processing and the data-handling chains - used for the experimental phase - allowing a large saving of resources.

5.2 Space-based Monostatic Radar

For what concerns the space-based architectural line, the second step - after this theoretical phase - should be the transition to the experimental-to-operative phase. Also for this architectural line, the low cost driver guides the designer to start from an existing millimeter wave radar; on this way, for what concerns the sensor, only the technical aspects for space application have to be solved.

Finally, it shall be necessary to design the up and down-link channels and the relevant TT&C stations; the reuse of existing stations appear now technically feasible, in both cases of free-flier and/or ISS platform.