WARDEN
W-BAND ADVANCED RADAR
FOR
DEBRIS EARLY NOTIFICATION

R. Battaglia[1], F. A. Pirillo[2], M. Ferri[2], F. Sarullo[3], A. Di Felice[3], M. Demeo[4], G. Tornaghi[4]

(1) Italian Space Agency, Rome. Italy – rbattaglia@asi.it
(2) Oerlikon Contraves S.p.A, Rome, Italy – f.pirillo@oci.it, m.ferri@oci.it
(3) Telespazio S.p.A, Rome, Italy – francesca_sarullo@telespazio.it, alessandro_difelice@telespazio.it
(4) Laben, Milan, Italy – mdemeo@webmail.laben.it, gtornaghi@webmail.laben.it

ABSTRACT

The understanding of the debris situation will be improved by the determination of the size, shape mass and attitude of orbiting objects for the assessment of the flux and collision rates and by the analysis of fragmentation laws after explosions or collisions of space objects.

On the basis of national industrial technological know-how, the Italian Space Agency (ASI) has founded a pre-feasibility study for monitoring small space debris directly in orbit as an experimental mission on-board of International Space Station (ISS) by using an advanced millimetre wave radar sensor.

The proposed experiment, described in this paper, offers several opportunities both in technological field (possibility to on-orbit qualifying of millimetre waves system and critical components) and in scientific field (completion of catalogue of centimetre and sub-centimetre space debris). It is aimed to validate the concept of future stand-alone on-orbit space based radar devoted to the detection of very small debris population.

1 SYSTEM & MISSION DESIGN ASPECTS

1.1 Antenna Pointing

First of all the debris flux for debris having diameter greater than 1 mm has been analysed according to the MASTER 99 model on the International Space Station orbit in the time interval July 1 2001 – June 30 2002 (just as indicative interval). The orbit is supposed to have an average height of 450 km, eccentricity 0,01 and inclination 55,0°, that is the ISS one.

The Figure 1.1 and the Figure 1.2 let understand which are the directions providing the faster debris approaches; more in detail the second of such drawings shows, as it is intuitive, that the closer to the ram direction is the approach, the greater is the relative velocity.

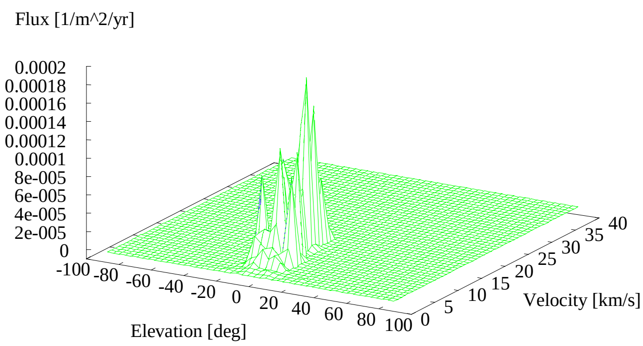

Figure 1.1 - Debris flux as function of both local elevation angle and approach velocity

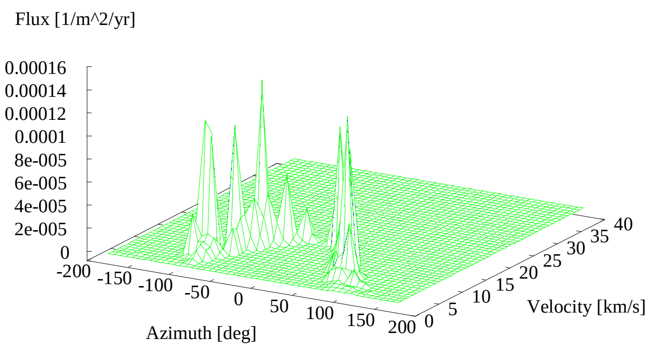

Figure 1.2 - Debris flux as function of both local azimuth angle and approach velocity

Summarising:

- the relative velocity modules are usual for the LEO region (5 – 15 km/s);

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

- the great part of the approach happens on the ISS local horizontal plane;
- the flux is rather spread with respect to azimuth.

Therefore, possible orientations of the antenna boresight, are:

1. *El* = 90° (zenith) or *El* = – 90° (nadir): in these cases almost all the approaching debris would have a tangent velocity with respect to the radar;
2. *El* = 0° and the azimuth equal to that of a debris flux peak: in this case some debris would have a velocity normal to the boresight, others would approach the sensor almost in the radial direction.

Concluding, as a compromise between the two previous solutions, the antenna sensor in this experimentation will be oriented at *El*=45°.

1.2 Mission Aspects: Objectives in Science, Application or Technology

The proposed experiment concern the installation of the millimetre-wave sensor on the Integrated Truss Assembly (ITA, S3/S4), on board of the ISS, or for instance on the Columbus External Payload Facility.
The proposed duration of the scientifical experiment should be at least 9 months, in order to have a significant data base of debris to allow an accurate validation of such 95 GHz radar instrument installed on board the space platform at 450 km altitude and 51.6° inclination.
The aim of this mission is to demonstrate that by using millimetre wave frequencies, it is possible to detect very small debris in orbit, in a diameter range from few millimetres to few centimetres. The use of 95 GHz radar (wavelength 3.33 mm) is essential to allow the observability of such small debris thanks to their higher reflectivity achievable at these frequencies.
This can be accomplished by employing a radar sensor that exploits the more modern technologies available at millimetre waves band, designed and presented in this document, as an instrument to be installed for demonstration purposes on ISS, and, more precisely, on an Express Pallet Adapter.
This feasibility study allowed a preliminary design of such radar instrument demonstrator, finalised in the future to important applications as such as for instance on-board surveillance and acquisition systems for early warning and detection of unforeseen debris, important for collision avoidance manoeuvres.

Among the other applications, it is important to underline the one concerning stand-alone flying surveillance and acquisition satellite, to improve the knowledge of the very small debris population, particularly in the diameter range 1 – 10 cm.
The proposed experiment gives, among the others, the possibility to experiment millimetre waves components (i.e. High Power Amplifier, Front End with MMIC technology, etc.) in the space environment, and then, to deeply investigate the application of millimetre wave technology to the future space missions. The main areas that can benefit from this technological developments are:

- components space qualification;
- design techniques and simulations;
- measurements and calibration techniques.

Other possible follow-on can be envisaged in the future telecommunication systems, radiometers and beacons for propagation studies.

2 ON-ORBIT SEGMENT: THE WARDEN INSTRUMENT

The WARDEN instrument is a space based sensor working at millimetre wave frequency (95 GHz) that collect radar space images (range profiles) to be sent to the Ground Segment equipment for further elaboration finalised to extract possible debris or other objects (in terms of angular position and range). Obviously, this data will be correlated to the ISS position data provided by the on board NAVAIDS.

2.1 General description

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 μs 13-Barker coded pulses and the longer one is 12 μs 36-Legendre coded pulse. The pulse codification has been necessary in order to improve the range resolution, 50 m in such configuration, and simultaneously to optimise the range coverage by maximising the transmitted energy.

Due to the power consumption requirements on ISS board, the maximum consumption allocated for the transmitter unit is 300 W that means, considering 10% as typical value for the tube efficiency, to transmit 30

W as average power. So as consequence, for the longer pulse (12 µs) the maximum PRF value achievable is 2500 Hz , that is 400 µs as pulse repetition time (PRT). If more power consumption is available on ISS board, for instance when the other experimental equipment on the same ExPA have been switched off, then it is possible to increase the average transmitted power up to 100 W (with 40 µs pulse length) and then to improve the range performance of WARDEN instrument.

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 285 km as overall maximum unambiguous range covered.

During the transmission of the 12 µs long pulse at frequency F1, the receiver front-end will result protected giving arise to a near blind zone of about 6 km radius. 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 µs length at 10 µs 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 radar receiver is based on a completely coherent receiving chain. It is mainly composed by a Low Noise Amplifier (LNA) having a large pass band filter in order to receive the four transmitted frequencies all together. The received signal is down converted by mixer and then sampled to be converted in 8 bit digital format. The first processing consists in a classical moving window Fast Fourier Transform (FFT) elaboration to make the observation time independent on the frequency of the transmitted pulse. The complex digital samples at the output of FFT block are digitally compressed in frequency domain according to the transmitted pulse code, integrated according to the frequency used inside the debris observation time and then processed to extract the module. The debris will give detection if at least one out four output of module extractor (one for each frequency used) will overcame the selected threshold. After the detection occurrence, an estimation of the debris range and angular position will take place.

The main parameters of the WARDEN millimetre-wave radar sensor are summarised in the following Table 2.1:

Table 2.1 – WARDEN Sensor parameters

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 µs ,12 µs
Frequency	95 GHz
Antenna Diameter (Cassegrain Monopulse)	1 m
Mismatching Loss	1 dB
Beam shaping Loss	1.6 dB
PRF (stagger)	2.5 ÷ 100 kHz
A/D conversion Loss	0.8 dB

2.2 Performance

In the Figures 2.1 and 2.2 the Range vs Detection Probability performance evaluated for debris having diameters respectively of 1 cm and 10 cm have been represented when longer transmitted pulse (12 µs) is used. The evaluation has been performed considering 10^{-6} as probability of false alarm (pfa) and the debris object like a disk shaped Swerling 1 fluctuating target.

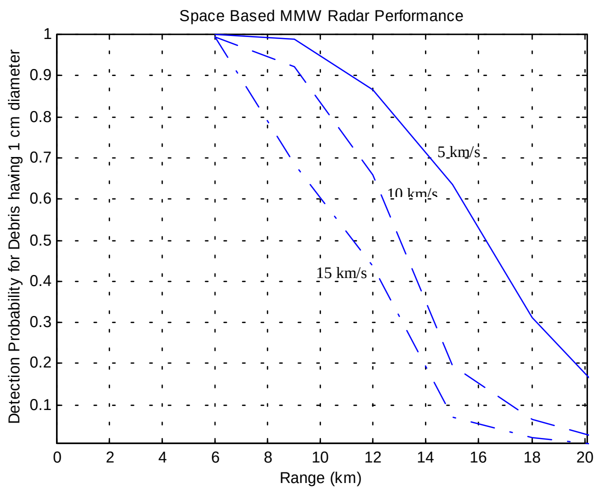

Figure 2.1 - Range vs Detection Probability for 1 cm debris by using longer pulse

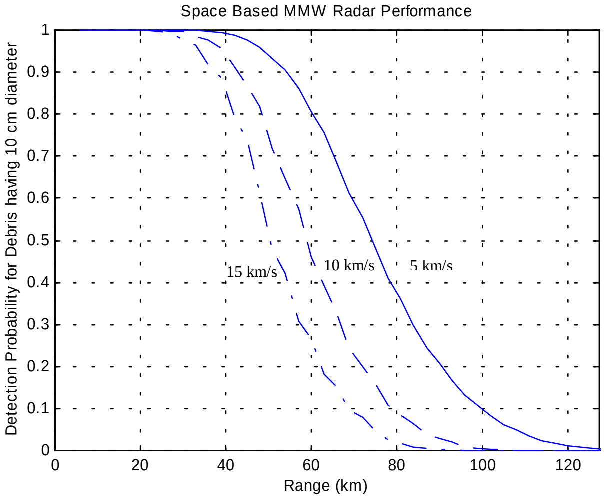

Figure 2.2 - Range vs Detection Probability for 10 cm debris by using longer pulse

In Tables 2.2 and 2.3 have been reported the range performances evaluated respectively for the 12 µs and 40µs pulse length cases.
In [1] has been evaluated also the angle accuracy in degrees (for both elevation and azimuth planes) vs distances from the sensor, for three velocity values 5, 10, 15 km/s and respectively for debris having 1 cm, 10 cm and 50 cm diameter.

Table 2.2 - Range Perfomance (12 µs Pulse Length)

PD (%)	RANGE PERFORMANCE (km)		
	0.5 cm Debris		
	5 km/s	**10 km/s**	**15 km/s**
90	6.8	5.5	4.7
50	10.2	7.9	7.1
	1 cm Debris		
	5 km/s	**10 km/s**	**15 km/s**
90	11.1	9.3	6.9
50	16.3	13.0	11.3
	10 cm Debris		
	5 km/s	**10 km/s**	**15 km/s**
90	54.3	42.7	37.6
50	74.2	58.9	50.5
	50 cm Debris		
	5 km/s	**10 km/s**	**15 km/s**
90	158.7	126.2	109.7
50	217.0	172.3	150.3

Table 2.3 - Range Perfomance (40 µs Pulse Length)

PD (%)	RANGE PERFORMANCE (km)		
	0.5 cm Debris		
	5 km/s	**10 km/s**	**15 km/s**
90	9.7	8.5	6.8
50	14.4	11.1	10.2
	1 cm Debris		
	5 km/s	**10 km/s**	**15 km/s**
90	16.5	12.7	10
50	22.7	17.4	15.8
	10 cm Debris		
	5 km/s	**10 km/s**	**15 km/s**
90	76.6	60.7	54
50	104.6	82.5	72.6
	50 cm Debris		
	5 km/s	**10 km/s**	**15 km/s**
90	223	176.4	154.8
50	304.7	242.7	211.7

2.3 Units Composition

The WARDEN Radar Instrument is composed by the following functional units, all deeply described in [1]:

- Antenna Unit (AU)
- TX/RX Switch Assembly
- Receiver Unit (RXU)
- Transmitter Unit (TXU)
- Frequency Generation Unit (FGU)
  - Control & Processing Units
  - Digital Signal Processing Unit (DSPU)
  - Space Time Adaptive Processing Unit (STAPU)
  - Pre-Data Processing Unit (P-DPU)
  - Instrument Communication & Control Unit (IC^2U)
- Power Distribution Unit (PDU)
- Express Pallet Adapters Communication Interface (EPACI)
- Express Pallet Adapters Power Interface (EPACI)

2.4 External Interfaces

A preliminary trade-off has highlighted that the sensor instrument actually does not need a Coarse Pointing Device. It is fixed pointed toward a pre-selected direction (45° off the zenith as elevation angle and ISS velocity direction as Azimuth angle) for all mission period. In the Figure 2.3 is represented a preliminary 3D view of the WARDEN sensor instrument.

2.4.1 Mechanical interfaces

The instrument will be located on one Express Pallet Adapter (ExPA) of the International Space Station (ISS). The instrument, including any support or mounting plate, shall not exceed ExPA envelope (863 mm x 1168 mm x 1244 mm), in both static and pointing conditions. The instrument will be composed by four mechanical part: 1) supporting plate to interface the instrument with the adapters; 2) antenna reflector with its mechanical support, 3) the front-end machined box which contain TXU, RX/TX switch assembly, RXU, 4) the electronics cabinet which contains the PDU, FGU, Control & Processing Units, EPA-P I/F, EPA-C I/F.

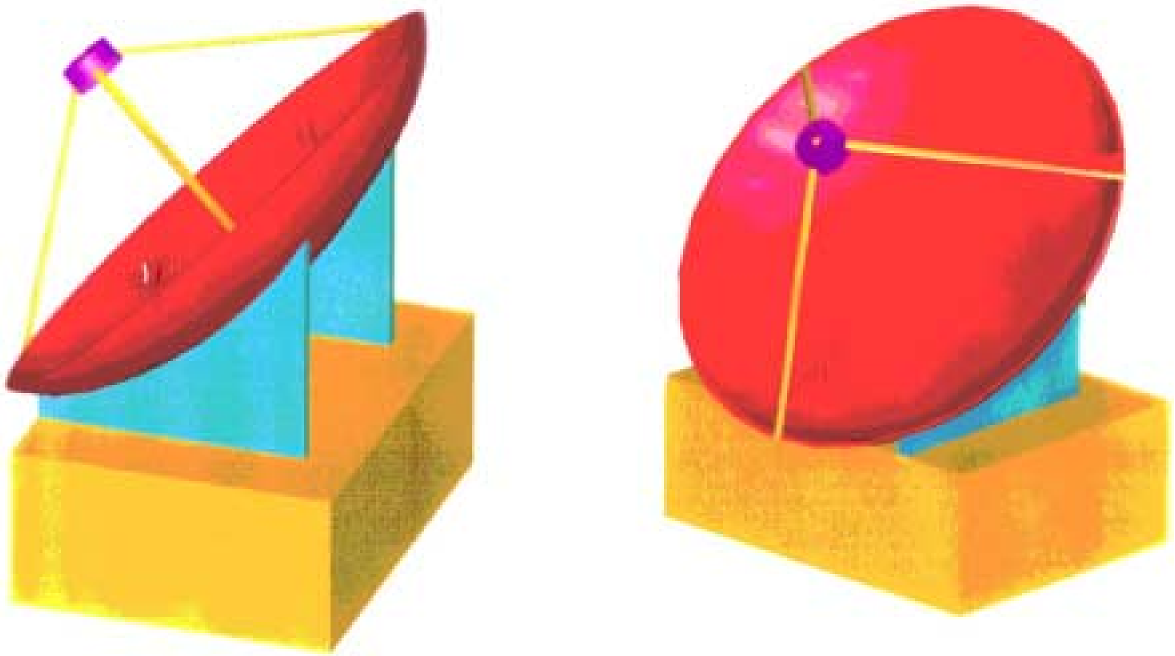

Figure 2.3 – WARDEN Instrument mechanical layout

The total mass of WARDEN radar instrument is less than 180 kg.

2.4.2 Electrical Power interfaces

At the level of the EXPRESS Pallet Adapter the following are available for payloads:

- 2 outlets rated at 2.5 kW@ 120 V (total EXPRESS Pallet allocation); or
- 2 outlets rated at 500 W @ 28 VDC (50% of EXPRESS Pallet allocation); or one of each (with a ceiling of 2.5kW for payloads)
- 2.5 kW is the global capacity for the total EXPRESS Pallet (ExPA) payload complement and has to be shared by 6 EPAs. The total power consumption of the WARDEN instrument will be less than 500 W @ 28 VDC.

2.4.3 Data Handling

Data, as well as telemetry, can be transmitted to the ExPA through the Ethernet interface. Signals shall meet requirements of the IEEE 802.3 (10BASE-T) specification.
In this case, Warden should interface the Payload Ethernet Hub Bridge (PEHB).

Communications via Ethernet could use the software protocol Transmission Control Protocol/Internet Protocol (TCP/IP) and Telemetry and Commands to/from shall be packed as specified in TBD. The WARDEN SW could transmit at predetermined time interval, experiment dependent, the HK and Debris data properly formatted as per TBD. Therefore, no request has to be sent to WARDEN to obtain the data.
Otherwise, a minimum I/F protocol should be foreseen between ISS and WARDEN to ask the Debris and HK data.
The amount of data to be transferred strongly depends on Debris detection events.
Considering the worst case, before mentioned of 4.74 Mbyte reduced to 1.2 Mbyte after compression (75% as

typical value considering that only few range bins will be involved by the debris trajectory), we get an affordable quantity of data to be transferred. Let us suppose now the events would be in order of one per second, the data rate will become about 9.6Mbit/s. Again a manageable quantity by Ethernet, providing that the LAN would be time available.
The availability of two locations and the possibility to store the data in SSMM and to pre-process it in PDPU suggests the use of MIL-STD1553B for TL/TC and Ethernet for debris data.

3 GROUND SEGMENT ARCHITECTURE

Due to Warden mission requirements, the Ground Segment Architecture has been defined based upon the extensive use of existing infrastructures and facilities both for Communications to/from ISS and for Sensor Monitor & Control (hosting in a multi-mission Control Centre) and for Sensor Data distribution to Users.
The Warden Ground Segment will collect the WARDEN sensor downstream that is the combination of both sensor raw data and telemetry and will send commands for sensor remote control by interfacing the ISS Ground Segment via a dedicated communication link. The Warden Ground Segment will be in charge of performing sensor raw data post-processing for the detection, observation, spatial distribution, classification and distribution to the users of Debris Data and, moreover, it will be in charge of sensor monitor (Telemetry) and control (Tele-command) in order to prepare the debris measurement campaigns, to set and manage the instrument and to check the instruments status through the housekeeping Telemetry.

3.1 Introduction

The Warden Ground Segment includes three main subsystems:
(1) the dedicated communication link (ASINET) to interface the ISS Ground Segment to Warden Control Centre;
(2) Warden Control Centre (included in an existing hosting multi-mission control centre) in charge of carrying out both the monitor (Telemetry) and control (Telecommand) and raw data post-processing of the Warden radar sensor, in order to prepare the debris measurement campaigns, to set and manage the instrument, to receive housekeeping Telemetry, to check sensor status and to direct towards the detection, observation, spatial distribution and classification of Debris Data (Raw Data);
(3) the Scientific Data Centre (ASI SDC) for Debris Data distribution, interfacing with the Users who can access (via INTERNET) in order to get information, products and services.

3.2 Warden Control Centre high level description

The WARDEN Control Centre can be considered made up of a set of components which represent the different modules devoted to perform the main functions/operations at ground level needed to manage the WARDEN Mission both in terms of sensor monitor & control and data management.
The instrument collects the space images (range profiles) to be sent to the Ground Segment equipment for further elaboration finalised to extract possible debris or other objects (in terms of angular position and range). Obviously, this data must be correlated with the ISS position data provided by the on board NAVAIDS.
Once the Warden Control Centre will receive Warden downstream it will separate scientific data (sensor raw data) from housekeeping Telemetry, so as to provide raw data post-processing for determining the distribution of the orbital velocities of the detected space debris, a data handling for determining the relative orbital data (orbit altitudes and inclination) and an archiving function for data distribution to the Users.
Warden remote control is based on time tagged telecommands, which are sent to the NASA Ground Segment via the ASINET communication link, uplinked during the visibility period and executed later on.
Time tag telecommands require accurate correlation between the on-board ISS reference time and UTC. The planning activity requires the development of a Mission Planning and Coordination Module. On the other hand, amount of data acquired needs to be correlated with ISS position to have debris in an absolute reference system and needs a dedicated archiving strategy as well as a complex data processing in order to satisfy the Users requests. This generates the Products Database where all the Users can access to Debris Data and require Services. Three different functions have been highlighted which enhance the requirement of three independent modules: WCS (WCS, standing for WARDEN Control System), MCF (standing for Mission Control Facility) and DDP (DDP, standing for Debris Data Processing).

- MCF for general planning and coordination
- WCS for direct WARDEN monitor and control activities
- DDP for Debris Data management dealing with user requests and with final data/product processing and delivery.

Thanks to the above rationale, the present approach deals with three functionally separate modules. The same logic leads to the assessment of the Debris Data and housekeeping data acquisition strategy. Current baseline for acquisition and processing is to use the ASINET as gateway.

4 CONCLUSIONS

The feasibility of a radar instrument working at 95 GHz to detect very small space debris has been investigated and analysed in this document.

First of all a study about the space debris population around the ISS orbit has been taken under consideration by analysing the debris flux and by determining the preliminary design and mission parameters for WARDEN instrument, as for instance the pointing angle of the antenna reflector.

A technology survey has been also performed to individuate the state of the art in the millimetre wave frequencies band, with particular reference to the transmitter, that is the EIKA tube, the FGU, the RX/TX switch assembly and RX unit. Particular attention has been devoted to those components to be still qualified for space mission, like for instance the EIKA tube.

The proposed solution for the ISS on board experiment will be basically composed by two segment: the on orbit segment, that is the payload, and the ground segment.

The on-orbit segment deal with a radar sensor working at 95 GHz which represents a good trade-off between to satisfy the limited power consumption available on ISS ExPA adapter and to have significant range and detection performance necessary for the success of the overall mission, with particular reference to the scientific results. If more source power will be available on the ExPA, for instance because the other experiments have been switched off, the instrument will be able to radiate much more energy and to perform better detection capabilities. The design of each unit of the WARDEN instrument has been deeply analysed in terms of feasibility and technological risk, by putting in evidence some critical areas, especially for what concern in-wave components, LNA, RX-TX separation, 82 GHz local oscillator, A/D converter and DSP. In the overall radar system design major emphasis has been given mainly to the weights, the overall dimensions, and to the EMC problems due to the simultaneous presence of other experiments on the same ExPA.

For the ground segment, a preliminary architecture has been proposed based upon the extensive use of existing infrastructures and facilities and including a Warden Control System mainly for all concerns on board payload support, a Mission Control Facility for the general planning of the Ground and Space resources, and a Debris Data Processing devoted to perform all the activities relevant to the provisioning of products and services based on payload according to user request.

In conclusion, it is important to underline that the proposed WARDEN experiment offers several opportunities both in technological field by giving the possibility to verify the use of millimetre waves components in space environment helpful for future ESA components qualification plan, and in scientific field to validate the concept of a future stand-alone flying on-orbit space based radar devoted to the detection of very small debris population.

5 ACKNOWLEDGEMENT

The feasibility study described in this paper has been entirely funded by the Italian Space Agency (ASI). A special acknowledge is for the University of Rome "Scuola di Ingegneria Aerospaziale, Gruppo Gauss", in particular Prof. F. Graziani and Ing. M. Porfilio, for its contribution about the debris environment around the ISS.

6 CONTRIBUTIONS

This study has been performed by the contributions from:

- OERLIKON CONTRAVES for:
  - Mission and system definition
  - Installation on ISS (mechanical part)
  - Safety aspects
  - Technology aspects.

- TELESPAZIO for:
  - Frequencies allocation
  - Ground Segment and Ground Data Processing
  - Payload Remote control and monitoring.

- LABEN for:
  - On board data elaboration and related technology aspects
  - Installation on ISS (electrical part).

7 REFERENCE DOCUMENTS

[1] *WARDEN Final Report*, Oerlikon Contraves Internal Document RR 402 397 AV.