New Perspectives in the WAVE W-Band Satellite Project

A. Jebril[1], M. Lucente[1], T. Rossi[1], M. Ruggieri[1], S. Morosi[2]

[1]University of Rome “Tor Vergata”, Dept. of Electronic Engineering
Via del Politecnico 1, 00133 Rome-Italy
Tel: +39 06 7259 7258, Fax: +39 06 7259 7455, e-mail: ruggieri@uniroma2.it
[2]University of Firenze, Dept. of Electronics and Telecommunications
Via di S. Marta, 3, 50139 Firenze-Italy
Tel: +39 055 4796 485, Fax: +39 055 472858, e-mail: morosi@lenst.det.unifi.it

Abstract. In 2004 ASI funded phase-A of the WAVE satellite mission, a feasibility study to design and develop a W-band geostationary payload. The aim was to perform experimental studies of the W-band channel and possible utilization in satellite data communications and data-relay services. The next phase of this project will address the experimental-only nature of W-band and the strategic relevance of making investments towards the development of the payload by performing preliminary experiments, such as the Aero-WAVE mission. The Aero-WAVE mission is presented as a basic test to provide the necessary measures leading to the development of the primary mission into GEO orbit. Aero-WAVE is a scientific payload that operates in W-band. It will be embarked on-board a stratospheric platform or High Altitude Platform (HAP) in order to perform a first test of the channel behaviour at an altitude of about 20 km. The stratospheric platform is a high altitude aircraft known as the M-55 Geophysica, a Russian aircraft well known in the atmospheric research environment and the European scientific community since 1996. The M-55 Geophysica will be equipped with the payload instrumentation to carry out the measurements. These measurements and the resulting data provided throughout the Aero-WAVE mission will give good indications of the channel behaviour at different weather conditions and at different locations within the GEO-WAVE coverage.

1 Introduction

During the last few years, the growth of innovative multimedia services have led towards the need to explore higher and higher frequency bands such as W-band (75–110 GHz). This unexplored frequency range could satisfy and improve the advanced and innovative services allowing high-volume data transfers. Therefore, it is becoming more and more necessary to exploit this frequency band which can be considered as the new frontier of satellite communications. Nonetheless, W-band potentialities are still unused due to the unknown atmospheric channel behaviour at these high frequencies since no satellite mission of either a scientific or commercial nature has performed any space experimentations at W-band frequencies.

Italy, through the Italian Space Agency (ASI), is one of the first countries that have made an effort towards the exploitation of W-band. It has financed two satellite projects; DAVID (DAta and Video Interactive Distribution) and WAVE

(W-band Analysis and VErification), in addition to other terrestrial and balloon-based tests and proposals towards the study of the W-band satellite channel.

2 WAVE A2: New Developments

W-band is recently considered as a "technological frontier"; thus representing the true challenge towards which the research community and the industry should concentrate their efforts.

The study of phase-A has been carried out [1, 2] to determine the feasibility of W-band to be used for the development of a telecommunications payload in a GEO orbit mission to provide the following:

- an experimental study on the propagation in W-band;
- preliminary experimentations towards the commercial utilization of the channel as a data relay.

This study has resulted in the feasibility of a W-band payload in both technical and commercial terms. It also showed that the development of a payload for telecommunications in W-band would be of a fundamental strategic importance from both technological and scientific points of view.

The second phase of the WAVE project A2, that is expected to start by the beginning of 2007, will carry out in parallel two main studies as depicted in Fig. 1; the first is a demonstrative study concerning the development of an experimental payload on-board a High Altitude Platform (HAP), referred to as Aero-WAVE, in addition to the development of a small nano-satellite platform. The second is a pre-operative study on the GEO-orbit outlined in the previous phase, and a payload in LEO-orbit on a dedicated micro-satellite platform. All the studies related to the development of the project WAVE-A2 phase will be focused on the following objectives:

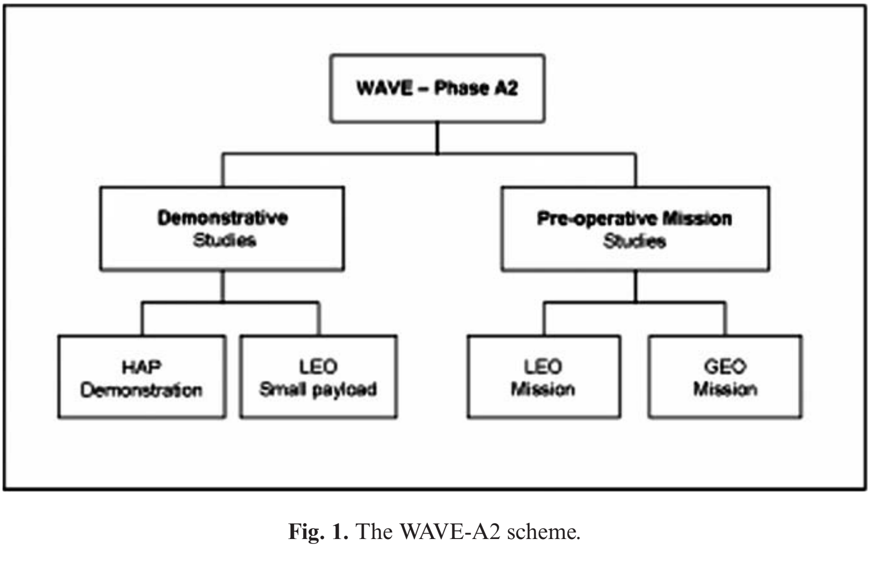

Fig. 1. The WAVE-A2 scheme.

- detailed definition of the proposed missions and of their payload;
- definition of the configuration and of the specifications of the whole system;
- analysis of the architecture TX/RX front-ends and of the antenna;
- evaluation of possible launching platforms and preliminary study of boarding;
- evaluation of the strategic technological elements and risk analysis;
- preliminary identification study of the earth segment (TT&C, Payload Control Centre).

3 The W-Band Experiment

The W-band experiment at this phase of the WAVE consists in the installation of a W-band payload with two RF transmitting channels on-board the Geophysica M-55 aircraft. The M-55 aircraft has been developed in Russia to be used as a high-altitude reconnaissance aircraft in operation since August 1988. Since January 2002, the M-55 Geophysica is supervised by the European Economic Interest Group (EEIG) Geophysica, providing services to the international scientific community [3]. The M-55 aircraft is currently the only subsonic aircraft in Russia and Europe performing long endurance flight at altitudes up to 21 km with the capability to perform long endurance high altitude flights (at altitudes of 17–21 km) providing services to a number of applications such as:

- scientific research of upper atmosphere layers;
- geomagnetic research;
- ecological monitoring;
- mapping and making thematic maps of land and water surfaces in different spectral ranges;
- retransmission of electromagnetic signals and localization of distress signals in global rescue system.

The scientific instrumentation is installed in special bays on-board the M-55 aircraft and operates during the flight in fully automatic mode. At cruising altitude the speed remains constant due to the flight altitude not exceeding 270 km/h. The flight radius of action can reach up to 1600 km.

The data transmission section operates at 94 GHz, and with a 92 GHz beacon, both used to provide the necessary signal reception experiments in W-band at the fixed earth station in Spino d’Adda and at the transportable station around Rome. The received signals will provide the necessary elements to analyze the channel behaviour at different weather conditions. Two flight campaigns are proposed; the first will be over the area around Rome where the transportable earth station will be used. This will give a good opportunity to provide different measurements in different locations. The second campaign is over the area of Spino D’Adda fixed station. The aircraft altitude for both campaigns will be around 20 km and the duration of each flight is about 4–5 hours. The flight route of all campaigns will have a diameter of about 10 km with an aircraft roll angle of 22°. The aircraft displacement data are shown in Table 1.

Assuming that the earth station is located perpendicularly below the center of the aircraft circulation orbit, and the on-board data transmission antenna has a beamwidth of 1.04°, the ground footprint has a diameter of 470.42 m. Therefore the

Table 1. M-55 aircraft flight data.

Cruising altitude	Turning radius	Angle of roll	Roll stability rate
20 km	10.76 km	22°	± 0.2°

corresponding elevation angle of both earth stations will be 61.72°. The on-board antenna will have an angle of 230.28° with respect to the yaw axis of the aircraft movement. The data transmission experiments are based on the transmission of a known bit stream saved in the on-board memory using a different data rate and different fixed coding-modulating scheme for every flight. The main goal at this stage is to counteract the large dynamic range of the expected attenuation by transmitting various rates of coded signals and the use of bit error control so that the power margins provision is traded for bandwidth and coding complexity. Therefore, in order for the W-band measurements to approach as much as possible the time-variant capacity provided by the W-band link and the strict requirements of the overall link quality and low Bit Error Rate (BER) values (BER$< 10^{-11}$), variable coding rates and hence the yielding variable information rates should be used. This can be accomplished by utilizing the flexibility of the rate-compatible punctured convolutional (RCPC) coding for better error correction adopted previously by the DAVID project [4][5]. This coding technique allows an encoder/decoder pair to change code rates without the need to make major changes to the hardware.

4 The Payload

The proposed payload design has been carried out considering the use of existing proved hardware to minimise failure risks, easy integration and test procedure. In this payload, it is possible to use solid-state power amplifiers (SSPA) given that there is no need for higher power transmission at this stage since the transmission distance to the HAP is relatively small. A 100 mW device would be suitable for the data transmission section, while a unidirectional antenna is proposed for the beacon in order to carry out the propagation experiment even in poor M-55 stability conditions. The beacon required power can be reached combining two or more 100 mW SSPA stages. In the up-conversion section, a 82 GHz master oscillator is used, based upon a reference source at 100 MHz. This reference source is also used to generate a 2 GHz signal from which, by means of multipliers, the 10 and 12 GHz signals are obtained. The first part of the payload is an on-board memory containing the bit stream to be transmitted followed by the modulation section in which the signal will be modulated by a 12 GHz Ku-band carrier signal obtained from the 82 GHz master oscillator previously proposed for the DAVID mission [5]. This modulated signal is then up-converted to the required W-band 94 GHz frequency using the 82 GHz master oscillator. The modulated signal is then amplified using a solid-state power amplifier, filtered and then sent through the antenna. Another important part is the beacon which will generate a 92 GHz sinusoidal signal to be transmitted for power measurements. To measure the power of the sinusoidal signals, the beacon must send a sufficiently stable signal. With the proposed minimal configuration, it is appropriate to use also radiometric equipment, in order to perform the so-called “bias removal”, specifically to estimate the “zero dB” attenuation level. This measurement technique, derived and validated in previous propagation experiments at lower frequencies (Olympus, Italsat) allows the calibration of the channel power, considering the clear-air attenuation due to presence of gases in atmosphere, which also affects the signal transmitted by beacon. At the receiver end, the signal is demodulated and the resulting baseband bit stream is compared with that of the originally transmitted (saved in the on-board memory) in order to determine the erroneous bits and hence, the BER value.

5 Simulation Results

Since all the atmospheric phenomena are strongly interdependent [6], the total attenuation is evaluated by combining the calculated attenuation values of each atmospheric effect separately. This implies a combination of the cumulative distributions of all contributions in a suitable way. The ITU recommendations; ITU-R Rec. P676-5 [7], ITU-R P840-3 [8] and ITU-R P618-7 [9] present a general method to calculate the total attenuation $A_T(p)$ from each individual attenuation contribution at a fixed value of percentage probability of time. The total attenuation, A_T (dB), represents the combined effect due to gases, clouds, rain and tropospheric scintillation. Given that the probability level p is fixed:

$$A_T(p) = A_O(p) + A_{WV}(p) + \sqrt{\left[A_R(p) + A_C(p)\right]^2 + A_S^2(p)} \tag{1}$$

where:

$A_O(p)$, attenuation due to oxygen
$A_{WV}(p)$, attenuation due to water vapour
$A_R(p)$, attenuation due to rain
$A_C(p)$, attenuation due to clouds
$A_S(p)$, attenuation due to tropospheric scintillation

Based on the above equations, the first estimates of the additional attenuation performed for the feasibility study of the payload at 94 GHz are presented below. The simulations were performed considering the two earth stations of Spino D’Adda and Rome at various elevation angles between 90° (best case) and 45° (worst case). Table 2 illustrates the estimated attenuation levels for the earth stations of Spino D’Adda and Rome at the minimum and maximum elevation angles 45° and 90°.

Figure 2 shows the simulation results of the percentage probability of time (x-axis dB) as a function of the total attenuation values (y-axis %) for various elevation

Table 2. Total attenuation values for Spino D’Adda and rome at 94 GHz (1% probability).

	Elevation angle		
Location	45∞	61.7∞	90∞
Spino D’Adda	13.72	12.19	11.69
Rome	14.92	13.33	13.04

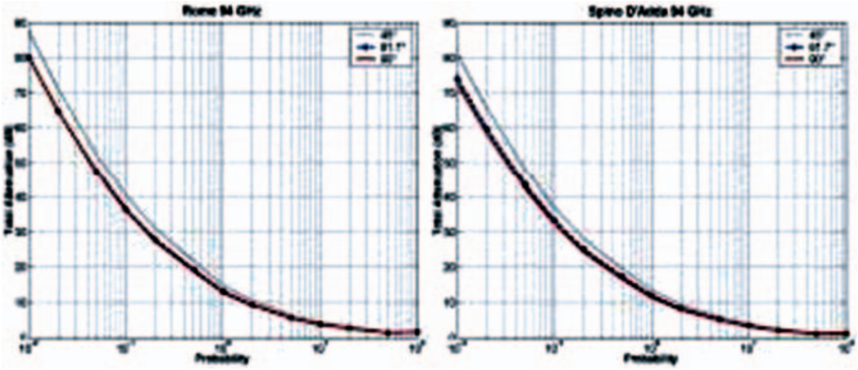

Fig. 2. Total attenuation estimated at 94 GHz (Rome and Spino D'Adda).

angles at the earth stations in Rome and Spino D'Adda at 94 GHz. It can be seen that the total attenuation values are significantly reduced for probabilities more than 5% of the time. The simulation was carried out using the available climatic data at Spino d'Adda and Rome. This means that it is feasible to establish the W-band link for limited availability for more than 95% of the time.

6 Future Perspectives in W-Band

In January 2004, a national directive has defined the new frontiers for the mankind with a "Vision for Space Exploration". The first step of this new challenge is the re-exploration of the Moon, focusing thereafter towards the Mars planet and other planets of the Solar System. At present, only a worldwide effort would afford to collect the necessary scientific, technological, human resources to face this huge project. The required expertise and know-how is very widespread, ranging from propulsion to communication systems up to the effects on astronauts living in space for long time. In this context, the use of terrestrial applications of W-band and scientific and technological results from WAVE experience could have a considerable advantage since no significant atmospheric effects are present outside the Earth.

A number of scenarios are foreseen for the return on the moon missions as shown above in Fig. 3, including the possible use of one or more W-band GEO (and possibly LEO) satellites to work as a data relay between rovers or base stations on the moon and the corresponding earth stations [10].

A likely scenario for the Moon mission could foresee the possible use of a number of landers and rovers on the surface in different regions, supported by one or more orbiters. Orbiters perform scientific observations with different instruments (active and/or passive), and support landers and rovers creating a communication infrastructure (data, telemetry, commands, etc.) between Moon and Earth. This could include many interesting applications that can be envisaged where W-band is the main actor, offering a key contribution in space exploration missions concerning:

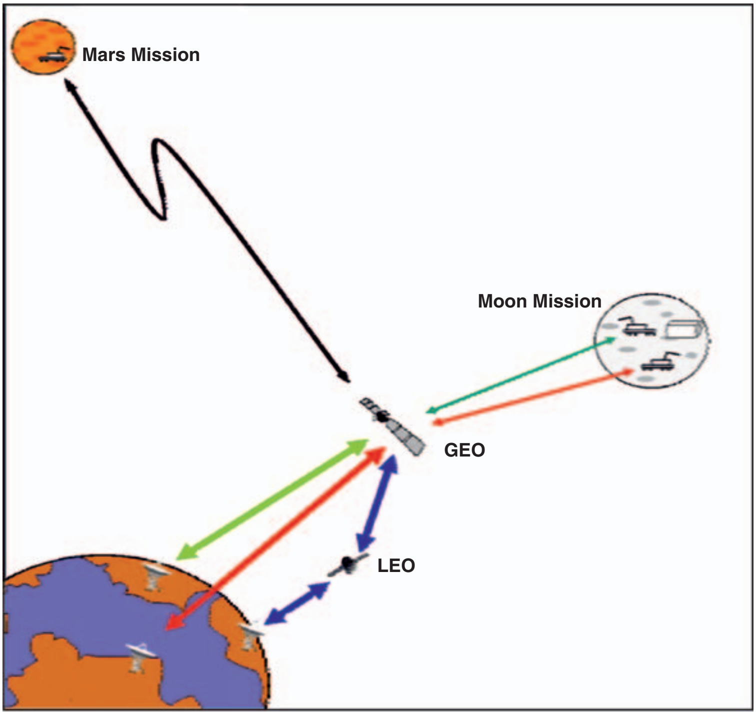

Fig. 3. A foreseen scenario for the exploration of the moon and planet mars.

- *Communications*—a W-band full space communication network can be used to exchange communications between orbiters and landers and/or rovers on the surface, between orbiters and ISS (International space Station) and/or other DRS (Data Relay Satellite) GEO satellites
- *Surface Survey*—orbiters can be provided with W-band radars for remote sensing, in order to produce high resolution surface images and to get multiple benefits such as searching and mapping for ice in polar regions and in darkest craters, very helpful in the creation of permanent bases on the Moon; and also identification of geological and geomorphologic features.

However, since the potential benefits of the W-band technology are affected by atmospheric attenuation in case of terrestrial applications, W-band can be fully exploited in space applications. Such a vision can be applied also to future exploration missions to Mars and beyond. Any long range space mission will be based on the use of CEV (Crew Exploration Vehicles), orbiters, landers, rovers, USV (Unmanned Space Vehicles).

Deploying W-band communication links between these vehicles will provide reliable, accurate, high rate, safe, secure data transmission and some additional advantages such as:

- Reduced mass and volume of components
- Small size of antennas

- Small antenna beamwidth
- Low power consumption

High resolution radar imaging from orbiters and satellites of potential landing and settlement areas (polar regions, crater bottoms) represents a fundamental preliminary step in the colonisation process of the Moon and Mars. USV can be used in the thin atmosphere of Mars for aerial radar survey and mapping of much broader surfaces than with wheeled rovers. In particular, Lunar orbiters and satellites offer favourable support for W band radar applications:

- absence of atmosphere
- much lower orbital speed compared to Earth (1:5)
- very low distance from surface
- static environment (no time constraints)

Under these circumstances, W-band radar imaging can offer the required resolution, at much more favourable conditions compared to medium frequency SAR (Synthetic Aperture Radar) solutions, resulting in a potential optimization of the synergy between radar and communication hardware.

We can also envisage applications related to safety-on-trip using high resolution radar for:

- detection and mapping of small debris
- rendezvous and docking operations

Moreover, energy beams for power transmission from the power plant (nuclear or solar) to users (ground based, orbiting or flying) could improve high focusing, pencil beam capability with smaller antennas.

The choice of W-band for the above applications might be preferred over the use of lower band frequencies considering the following advantages:

- availability of the technology and electronic components operating in W-band.
- reduced mass and size of components
- broad bandwidth and high data rates.

7 Conclusion

In this paper, an overview of the Aero-WAVE test is presented. A manned HAP known as the M-55 Geophysica aircraft will be used to perform a number of propagation experiments, transmitting an experimental W-band signal over the area around Rome and Spino D'Adda.

A description was provided on the payload to be delivered, and the main aspects of the experiments and the simulation results of the expected total attenuation levels at both earth stations are provided. These results show that the W-band link can be feasibly established to provide broadband communication services for 95% of the time, based on the available climatic and data attenuation values for each individual atmospheric effect. The results obtained during the Aero-WAVE tests are expected to help in the characterization of the W-band channel behaviour in different weather conditions at both, Spino D'Adda and Rome.

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