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EHF channel sounding for telecommunications applications via HAPs and balloons

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Abstract. During the last few years, the growth of innovative multimedia services demanding for more and more bandwidth have led towards the need to explore higher and higher frequency bands for communication services, such as Q-V band (35 − 50 GHz and 50 − 75 GHz, respectively) and also W band (75-110 GHz), especially for satellite applications. The Italian scientific community has so far gained a leading position in the use of higher frequency bands for satellite communications and has also funded studies for the design of communication payload in W band. To keep this leading position one fundamental step to properly design an operative communication payload is the propagation channel characterisation. Whilst there are data for characterising the propagation channel in Q-V bands, there are no experimental data for proper characterisation in W band. A feasibility study has been recently funded by the Italian Space Agency (ASI) to use a manned aircraft flying at 20 km, for preliminary channel characterisation. In this paper we investigate the possibility to use balloons for experiments aiming to collect data for channel characterisation. Main advantages and drawbacks of using this platform for the proposed experiment with respect to alternatives such as manned aircrafts and Low Earth Orbit (LEO) satellites for such a experiment are outlined. We start presenting the main results of the Aero-WAVE mission, funded by ASI and aiming to design a payload for setting up an experiment for preliminary channel characterisation of W band. This will guide us in defining the main advantages and drawbacks of the alternatives solution represented by the balloons. We can conclude that it would be possible and convenient to use balloons for the proposed experiment. Some issues arise but solutions can be easily implemented. The data that could be collected from the proposed experiment represent a very interesting results at international level for further developments in W band communications. The possibility to set-up such experiment in a short-time and low costs would be strategically important.

Key words. W band–EHF–high frequency–propagation–telecommunications–balloons

1. Introduction

In the last years the development of several broadband communication applications has created the need to allocate more bandwidth to the current and future envisaged services. Since frequency bands such as Ku, K, Ka bands are already crowded, it is mandatory to start exploring the possibility to use higher frequency bands such as EHF (Extremely High

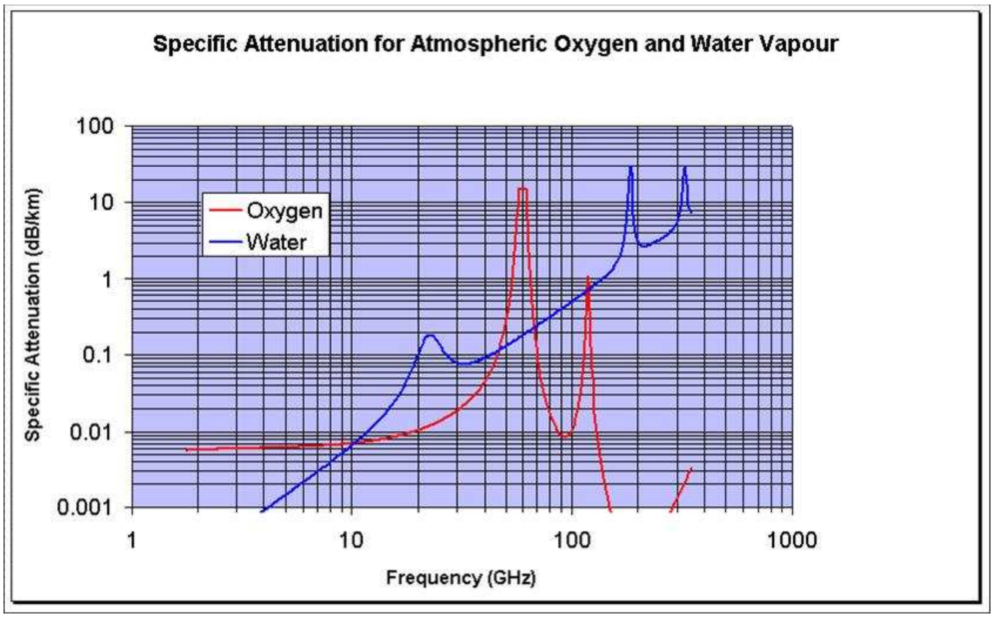

Fig. 1. Specific attenuation (dB/km) for atmospheric oxygen and water vapour.

Frequency) bands for communications. Such a range (30−300 GHz) covers the millimetre part of the electromagnetic spectrum, 10-1 mm respectively, and it is currently a still unexplored range in telecommunications. The reason is mainly due to two elements: the relatively poor development of components and equipment at commercial level operating at these frequencies, especially over 40/50 GHz, and the significant propagation attenuation mainly due to the atmosphere and troposphere precipitation, which affect the electromagnetic waves propagation (additional attenuation). Moreover, the atmosphere presents a significant impairment around 60 GHz due to the existence of a large absorption band of the oxygen which affects with its ”wings” all the range from 50 to 70 GHz. Figure 1 shows the specific attenuation for atmospheric oxygen and water vapour.

In addition, ITU regulations assigned the frequency slot 54 – 58 GHz to inter-satellite links, which operating at higher altitudes where atmosphere is extremely rarefied, presents a negligible attenuation.

In the last years significant improvements in microwave materials and processes have given an important boost to high frequency technology, allowing to consider applications at EHF band.

To properly design operative payloads in those frequency bands, the first step is an accurate channel characterisation. Whilst there are data for characterising the propagation channel in Q-V bands and the next steps are the studies of mitigation impairments techniques such as Adaptive Modulation and Coding (AMC), there are no experimental data for proper satellite channel characterisation in W band. A feasibility study has been recently funded by the Italian Space Agency (ASI), the Aero-WAVE mission (Cianca et al. , 2008) to use a manned aircraft flying at 20 km, for preliminary channel characterisation. It is one of the missions studied within the WAVE Project (AIAA Lucente et al. , 2008), (IEEE Aerospace conference Jebril et al. , 2008), an ASI study to design and to develop a W band telecommunication payload for channel characterisation and preliminary service evaluation.

In this paper we investigate the possibility to set-up an experiment for channel characterisation in W band via balloons. As it is shown in the paper, this would help getting those data in a shorter time and much lower costs. Some challenges arise mainly due to the low stabilisation of balloons and need of tracking. However, those challenges do not appear difficult to be overcome. Moreover, the payload and most of the design solutions foreseen for the Aero-WAVE mission over manned aircraft could be used for an experiment on a balloon.

The paper is organised as follows: after a first introduction, Section 2. outlines the importance of channel characterisation for communication applications in EHF. Section 3. shows an overview of the use of balloons for communication experiments; Section 4. shows main features of the Aero-WAVE mission; Section 5. presents main advantages and drawback of the use of balloons. Conclusions are drawn in Section 6.

2. EHF band for communications via satellite

The millimetre wave domain has been traditionally studied by physicists in cosmology and radio-astronomy. However, since '90s an increasing interest for W band has been demonstrated in technical fields such as radar systems; actually, this is the main application of W band in terrestrial systems. The exploitation of the intrinsic smaller wavelength in fact allows to achieve higher resolutions and hence the realisation of imaging at microwave frequencies (achieving resolutions of tenths of centimetres, as order of magnitude). In this domain, Rheinmetall Italy (ex Oerlikon Contraves) has developed a significant background and expertise through the design, the development and the deployment of millimetre wave radars for airport surveillance applications. A W band operative mini-radar (so called due to its compact dimensions) called SMART (Galati et al. , 1995) developed by Rheinmetall Italy was the first operated in airports. It was installed in 2001 at the Frankfurt Airport and a second one at the Venezia "Marco Polo" airport. Both radars are fully functional and are used for the control of air traffic on the airport surface (surface movement radar). SMART works at 95 GHz and has smaller dimensions and improved target detection with respect to similar radars.

Recently, W band has also been employed in space. NASA launched a new mission (2006), CloudSat, to study clouds and climate using a weather W band radar at 94 GHz; it was the first mission carrying a space-qualified high-power W band amplifier, a critical equipment for space applications at these frequencies. This satellite, currently operating in orbit, will be one of the six Earth Observing Satellite (EOS) foreseen for the "A-Train" constellation, dedicated to a coordinated and continuous observation of weather, climate, air quality.

The use of EHF band (30 – 300 GHz) for telecommunications represents an interesting opportunity to face the current and future increasing needs of the broadband scenario. Actually, increasing the operating frequency allows for many advantages, including increased available bandwidth, improved resolution and directivity which can be obtained for a given antenna aperture, reduced interference (due to the greater bandwidth availability and the reduced number of users). This means smaller, lightweight systems offering increased transmission capacity for communication systems or improved resolution for radar or imaging systems.

Specifically, EHF satellite communications, in particular Q/V bands (35-75 GHz) and W band (75-110 GHz), could bring important benefits such as:

- increased available bandwidth, with respect to saturated lower frequency band;
- higher security level in terms of protection and interference with respect to lower bands through the use of very narrow spot beams;
- mass and size saving, due to the smaller equipment guaranteed by the short wavelenght.

However, nowadays W band is still an experimental frontier in satellite telecommunication systems since no mission has been developed so far (just feasibility studies were carried out). Italy, through the Italian Space Agency (ASI), is one of the first countries that have made an effort towards the exploitation of W band for telecommunications, funding two projects recently carried out: DAVID and WAVE.

DAVID (DAta and Video Interactive Distribution), was a project aimed at the deployment of two scientific communication experiments on ASI PRIMA platform in Low Earth Orbit (LEO) (C/D phase proposal). One of the two experiments aimed at testing the feasibility of a satellite system for the exchange of a large amount of data through a 94 GHz data collection link and a hybrid LEO/GEO network.

The WAVE project phase A (W band Analysis and VErification) started in 2004 as feasibility study to evaluate the feasibility of a W band telecommunication payload for a geostationary orbit mission.

Both the studies concerned satellite links and foresaw the characterisation of the propagation channel at W band. Considering both the high cost of a satellite system and that the significant impairment of the atmosphere is due to lower part, the stratosphere, an interesting alternative approach to evaluate the channel behaviour is based on the use of stratospheric ballons or, more in general, HAPs (High Altitude Platforms) (Karapantazis , 2005).

EHF is also particularly attractive with respect to the realisation of portable terminals and smaller satellite payloads, for example in the context of space exploration, where mass and size are one of the most important missions driver. The exploitation of higher frequency bands for the possible provision of commercial services not only presents the main advantages above described but also some uncertainties. In fact, it is fundamental to investigate carefully dangerous areas of uncertainty and risk in order to avoid technological and market failures. Recent research activities evidenced relevant issues to be solved in the design of the W band physical layer (phase noise, high Doppler shift, nonlinear distortions and problems in carrier recovery). Moreover, the strong uncertainty about physical channel characterisation may represent potential "black hole" in the usage of W band in aerospace connections. However, the main drawback of EHF satellite links is due to the large atmospheric fade. Actually, the influence of the atmosphere on signal propagation at these frequencies is not negligible. Transmitted signals are affected as more as frequency increases (above 10 GHz) by atmosphere (absorption gaseous) and by weather conditions (especially rain and specifically hydrometeors). Main phenomena contributing to the atmospheric attenuation are the following:

- absorption of atmospheric gases (water vapour and oxygen);
- absorption and depolarization caused by the hydro-meteoric phenomena (water and ice particles);
- absorption of clouds;
- fast fading or scintillations and fast variations of the refraction index

The total attenuation in a satellite link is due to: space free losses (due to the distance) and additional attenuation. The latter one is due to the atmosphere. Estimates of additional attenuation are fundamental to establish a correct link margin to face bad weather conditions to which W band is sensitive. Therefore, we can conclude that the W band challenge is to understand the propagation channel behaviour, at present unknown due to the lack of experimental data. Actually, no measurements available at W band and no additional attenuation statistical or empirical models are available. However, a preliminary assessment of attenuation levels can be obtained using the models validated at lower frequencies,i.e. the ITU-R ones.

Such models have been used, for example, to obtain preliminary cumulative distribution of the attenuation. The figure 2 illustrates such a distribution. It reports the attenuation value that is not exceeded for a particular percentage of time (usually, 5 % or less), value used to set the margins in dimensioning the link budget (1st order statistics). In particular, the figure shows the additional attenuation for different elevation angles at 86 GHz for a ground station located in Rome.

Another open issue concerns with the higher layers of the ISO-OSI diagram. In fact, PHY-layer solutions targeted to provide high data rate transmissions with lower and lower

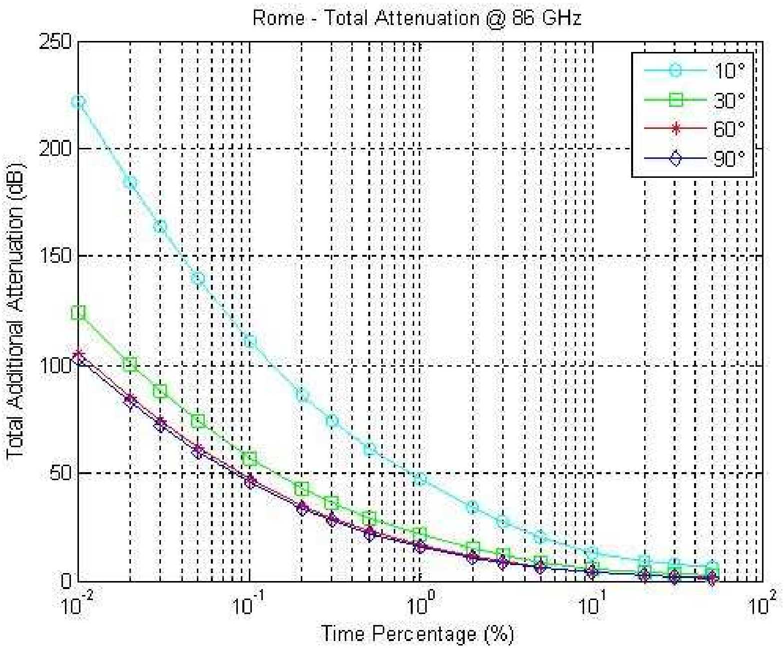

Fig. 2. Cumulative distribution of the attenuation at 86 GHz for different elevation angles.

bit-error-rates are currently under investigation. The exploitation of EHF bands for the provision of commercial services mainly depends on the verify of the possible employment of transport protocols (like satellite-TCP) able to support very high capacities of the order of some Gbit/sec and the potential mitigation of the effects of the round-trip-time (very high in geostationary satellite connections) representing the true bottleneck for aerospace connection capacity.

3. Balloons in the communication field

Balloons have been already used in the communication experiments. They represents a low cost solution for satellite channel characterization. In fact, the signal impairments, especially at EHF bands, are mainly due to the troposphere attenuation (rain, clouds, fog, atmosphere gases). The contribution of the higher part of the atmosphere, so rarefied, is negligible. Therefore, if balloons are posed above the troposphere, they allow to collect important data for satellite channel characterization.

In 1988 the University of Surrey undertook a feasibility study for the European Space Agency (ESA), to conduct a multi-band propagation experiment for Land Mobile Satellite (LMS) communication services at elevation angles greater than 50^o. Propagation measurements of about 6- 10 hours at $50^o - 90^o$ elevation angles were expected to provide reasonably representative data for high elevation angle characterization in LMS channel. Lower costs and more manageable logistics were the main reason to choose Balloons instead of Helicopter and Airships. The main drawback of balloons was the fact the elevation angle cannot be controlled. However, adopting particular flight strategy and mobile location area can help maintaining elevation angle within a desired range (Suzuki et al. , 2006; Butt , 2006). Moreover, balloons have been used to play the role of other kinds of High Altitude

Platforms (HAPs) such as airships and airplanes (manned or unmanned) in experiments that were meant to test the possibility to use those HAPs as a component of a communication network. There has been a lot of talking in the last 10 years about the use of HAPs as a component of the future telecommunication infrastructure since they have attractive advantages wrt satellite and terrestrial base stations: they appear in a roughly fixed position thus fulfilling the role of either a very tall radio mast or a very low geostationary satellite; they have low launch and maintenance costs and the deployment can be rapid: new HAPs and payload can be provided more quickly than new satellites or installing large terrestrial infrastructures; they are extremely flexible since platforms and payloads can be reconfigurated in order to satisfy various topologies of services during different periods and in different regions. In 2005, the European CAPANINA research consortium, led by the University of York, has used a stratospheric balloon for high altitude trials in northern Sweden on a broadband communication systems designed for HAPs. The Italian company Carlo Gavazzi Space coordinated the trials at the Swedish Space Centre at Esrange and took care of the a stratospheric balloon. Trials using radio and optical communications equipment were carried out, using a $12,000m^3$ balloon, flying at an altitude of around 24 kilometres for nine hours. The lightweight, low-cost, high speed broadband wireless access radio link equipment was designed and developed by the University of York to operate in the mm-wave band (28/29GHz). This supported data rates of 11Mbit/s and throughputs up to 4Mbit/s, using WiFi (IEEE802.11b), at distances ranging up to 60km. The trial was a multi-partner collaboration including University of York (UK), Carlo Gavazzi Space (IT), DLR (D) and CSEM (CH). Further research work continues and additional trials are planned in conjunction with the Japanese partners (NICT and JSC).

Moreover, a tethered balloon facility to address HAPS communication system and propagation blockage issues for use by UK industry and the research community has been conceived. The facilities can be used to establish the performance that could be expected from a High Altitude Platform based communication system, and to assist in an evaluation of the manner in which such systems would be operated in practice.

4. HAP for EHF channel sounding: the Aero-WAVE mission

As it has been previously mentioned, The troposphere attenuation, due to rain, clouds, fog, atmosphere gases, is the main phenomenon that could limit the exploitation of EHF frequency bands, in particular for W-band. Therefore, measurements collected by the HAP experiment could already give significant data for the design of future LEO/GEO missions in W-ban with the following advantages wrt satellite missions experiments:

- the set-up of the experiment requires less time (1 year wrt to 10 years of a GEO mission);
- the costs are lower with (around 250 MEuro with a manned aircraft).

ASI funded a study to design a payload in W band to be embarked over a Russian manned aircraft, Geophysica 55 from STM-Ltd, for a preliminary channel characterisation. The stratospheric platform is a high altitude aircraft known as the M-55 Geophysica (3), a Russian aircraft well known in the atmospheric research environment and the European scien-

Fig. 3. The M55 aircraft by MBD Ltd.

tific community since 1996. The aircraft altitude will be around 17-20 km. The flight route will have a diameter of about 10-20 km with an aircraft roll angle variable from 6^o to 26^o, due to the manoeuvers that have to be performed by the pilot in order to counteract winds upheaval. Figure 2 shows the mission scheme.

Specifically, the project aims at analysing the W band channel through two different experiments:

- Channel propagation experiment, including power measurements in order to create a first troposphere attenuation model (on both uplink and downlink);
- Data transmission experiment, including BER measurements in order to evaluate the W band channel quality (on downlink);

One of the main challenges of this mission on mannned aircraft was the stability of the platform. It is very important for communications in W-band to take into account the stability of the platform since the very high frequency used brings to a very small beamwidth (2-3 degrees) and footprint.

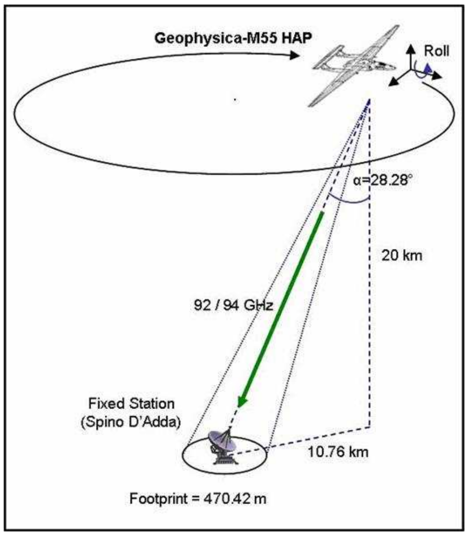

Fig. 4. AeroWAVE mission scheme

Therefore, a lot of attention has to be spent in the design of the antenna and the pointing system. Narrow beam high gain lens antenna with a mechanical pointing system could be controlled via two different approaches:

- tracking the ground station by calculating the correct pointing direction through an algorithm based on the a-priori knowledge of the station position, of the aircraft GPS positioning data and attitude data (roll, pitch and heading angles) provided by M55 navigation system;
- maintaining a fixed pointing on the elevation plane through a Gyro-stabilization using a two-axis gimbal compensating roll and pitch offsets through rate sensors in each axis.

Other challenges to be considered are the following:

- Each flight has a duration of 5-6 hours. In this short time it is not easy to get significant statistical data under different weather conditions and seasons; this limits the significance of the collected data. Still these data can be used for useful preliminary evaluation;
- finally, lot of additional costs and precaution for the pilot must be taken into account. This makes the logistics less manageable.

Finally, experiments at different elevation angles would be important to verify the validity of theoretical models (i.e. secant law) and they can be easily performed.

5. Balloons for channel sounding: advantages and challenges

What about using a stratospheric Balloon instead of a manned aircraft?

The weight of the designed payload for the Aero-WAVE mission is less than 15Kg. Therefore, it can be easily embarked over a simple a low cost balloon and a good part of the work done on the Aero-WAVE mission could be reused in the this new experiment based on balloons. Duration of each flight could be from

6-8 hours to 10 days depending on the type of balloon and on the latitude with respect to the 4-5 hours of a manned aircraft as M55. The higher lasting of balloons flight is likely typical during Antarctic flights. However, such a location could be not so much useful for a W band characterisation due to the very dry atmosphere and the very low rain rate. As for the manned aircraft, it is possible to have different campaigns at different elevation angles. One main advantage can be identified: there is not need for a pilot and hence, lower cost and less logistics problems (no need to have complex procedure to avoid radiation shield) can be foreseen. However, some challenges need to be highlighted. The problem of the stability of the platform, already outlined in the Aero-WAVE mission, is even more challenging here. For communications experiments, the best would be to have the balloon fixed in one position and this is not possible. However, the requirements in terms of pointing capability for our propagation experiment are expected to be less stringent than the ones for an experiment requiring a telescope. Therefore, solutions foreseen for other missions should be fine for this communication experiment. Moreover, the choice of the launch area (for instance, Antartic areas are not interesting for our experiments) and the flight strategy (kind of circle of a certain diameter) have to be made very carefully

6. Conclusions

In this paper a preliminary overview of EHF telecommunication experiments has been provided, focusing on the use of HAP platform and in particular balloons. Ballons have been already successfully used for both propagation and communication experiments both for satellite and HAP. A study of propagation and communications in EHF band via balloons would be very significant and could have a great strategic importance:

- first significant data for channel characterization in W band;
- tests on the use of this pretty new technology;

A possible future experiment with balloons could reuse most of the work already done for the design of a payload for a manned aircraft (Aero-WAVE mission). Other challenges have been identified which require a deeper analysis. However, feasible solution are foreseen and we can conclude that balloons represent an very attractive solution for channel sounding in those not much explored frequency bands.

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