Experimental Missions in W-Band: a Small LEO Satellite Approach

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***Abstract*—W-band (75-110 GHz) is proposed nowadays as a valuable alternative to intensively-exploited Ku and Ka bands for high-speed transmission over satellite networks. In such a framework, some experiments are being carried out, which are targeted to verify the feasibility of exploitation of W-band for broadband service deployment. From a theoretical viewpoint, the large bandwidth availability and the scarce amount of interference typical of W-band should guarantee high capacities. Nevertheless, many crucial aspects are still to be carefully investigated, e.g.: signal propagation issues, RF impairments, choice of modulation and coding, efficient antenna design, etc. In this paper an overview is made on the LEO nano-satellite mission IKNOW (In-orbit Key-test and validatioN Of W-band). IKNOW mission is an on-going advanced feasibility study part of an Italian Space Agency Project, named WAVE (W-band Analysis and VErification), coordinated by Department of Electronic Engineering of University of Rome "Tor Vergata". The main objective of IKNOW mission is to tackle some of the unexplored critical aspects concerning W-band satellite transmission. In such a perspective, IKNOW should be regarded as a "pilot mission", whose results will be used for a first uplink-downlink satellite channel characterization, in-orbit validation of W-band technology, and space qualification processes. The paper is focused on the research work carried out in a preliminary phase of IKNOW study and will consider also a number of elements related to the mission configuration, payload architecture, link analysis, potential RF impairment factors and atmospheric effects. Proposed analysis and preliminary results shown can provide to interested readers the basic guidelines that will drive the practical implementation of IKNOW mission, as well as the most relevant issues to be faced by future developers of W-band missions using small LEO satellites.**

***Index Terms*— LEO, Mission, Nanosatellite, Payload, Communication, System, W-band, Satellite, EHF, microwave.**

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I. INTRODUCTION

IN the last few years research and development in telecommunications systems has been oriented toward the development of a Global Information Infrastructure (GII) aiming at spreading information and offering users a broadband access to a wide range of services. In such a scenario, satellite systems play a key role. In fact, due to their geographical covering and high throughput features, they fit well to any evolutionary integrated telecommunication architecture [1].

Exploring frequency bands with a larger bandwidth availability is a must in the view of matching the increasing demand for higher data rates, deploying novel telecommunication services with hard Quality of Service (QoS) requirements, and giving an answer to the strong need for integrating heterogeneous telecommunication systems [2].

As frequencies around the 60 GHz range cannot be effectively exploited, due to atmospheric absorption phenomena [3], the researchers community has shown a great interest in deploying broadband satellite systems for scientific and commercial services at W-band frequencies (75-110 GHz).

The exploitation of W-band for the deployment of commercial services in the aerospace segment presents some clear advantages but also some potential risks to be carefully appraised. Invoking one of the milestones of the Information Theory, i.e.: C.E. Shannon's capacity limit, we can say that the large amount of bandwidth available and the low interference level due to the scarce utilization of this frequency range should be translated in higher data rates achieved with arbitrarily lower error rates. Unfortunately, real channels (including satellite ones) are not generally Shannon channels (i.e.: characterized by known non-selective attenuations and additive Gaussian noise). Today, the performance behavior of any solution for data transportation over W-band frequencies across the troposphere is still unknown, since still no scientific and/or telecommunication mission has been realized, either on an experimental basis or in an operating mode. Truly, this strong uncertainty about physical channel characterization may represent a potential "black hole" in the usage of W-band in satellite connections. Effects of clouds, gases, and atmospheric turbulence on digital satellite transmissions at 90 GHz are not still well defined and realistically modelled.

Therefore, future missions targeted at studying the utilization of W-band should perform a first empirical evaluation of the troposphere effects on the W-band radio channel, and, at the same time, determine the future methodologies to accomplish systematic measurements and gain much more information about the involved signal degradations.

It is important to note that the only relevant satellite mission related to W-band exploitation is the DAVID (Data and Video Interactive Distribution) mission [4], established in 2000 by Italian Space Agency (ASI). In the framework of DAVID mission, ASI proposed a Data Collection Experiment (DCE) for the collection and the analysis of data from a W-band communication satellite system. It considers a Low Earth Orbit (LEO) satellite at about 570 km operating at 83.9 GHz and 94.5 GHz for downlink and uplink connections respectively.

Besides DAVID mission, other studies are considered in literature about W-band utilization for satellite transmission. For instance, in [5], an almost-zenithal satellite communication system is proposed for future W-band missions. It will exploit three different satellites to cover Japan and part of Australia for VSAT-VSAT connections, by adopting the frequencies ranging from 81 to 85 GHz for the uplink and from 71 to 74 GHz for the downlink.

Also the NASA Goddard Space Flight Center (GSFC) is interested in the exploitation of W-band in future interplanetary missions being "*The use of optical, Ka-band or W-band communications particularly attractive approaches because these technologies can support high data rates over very large distances with less mass, less power consumption, and smaller sizes than conventional RF techniques at lower frequencies*" [6], where an Integrated Interplanetary Network (IIN) involving a telecommunications infrastructure around Mars is foreseen, aiming at improving the data throughput. At same time, new generation spatial communication systems are analyzed to be employed for near-Earth future missions.

The above is the context in which the ASI mission "WAVE – W band Analysis and VErification" was conceived. Its scope is the development of a scientific W-band payload, where early studies carried out during the phase A of the WAVE project [7] have stated the feasibility of a W-band GEO payload to be used for high-rate broadband data transmission [8].

The phase A2 of the WAVE project [9] will consider among its various activities different research and development lines. In particular, together with the exploitation of the major GEO (basically studied during phase A) and LEO missions, two low cost experimental payloads using Commercial-Off-The-Shelf (COTS) components will be developed. The first one, named Aero-WAVE [9], will be embarked on-board a High Altitude Platform (HAP) known as M55 Geophysica by the Russian company Stratosphere-M Ltd, while the second one, named IKNOW (In-orbit Key-test and validatioN Of W-band), will be hosted on-board a small dedicated satellite platform. Both "light" payloads will support technical choices that will be taken to best set up the GEO and LEO pre-operative missions.

This paper is focused on the research and development activities concerning the IKNOW mission. The starting point of this study is a question: how can a nanosatellite flown alone contribute to the W-band characterization aiming at assessing the viability of this frequency band for future communication applications? In general, the W-band experiment objectives, currently considered by the scientific community aim at ([7]-[11]):

- Performing either downlink or uplink for gathering statistically meaningful propagation data, acquired, at least, from part of Italy;
- Assessing the viability of using the bandwidth for discontinuous packet data transmissions at data rates in the 1-100 Mbps range;
- Studying the feasibility of "gigabit satellite connectivity" over W-band.

To achieve the first objective a satellite either in a geostationary orbit or in any other (e.g. elliptical) orbit, providing a near-continuous ground terminal visibility, seems to be mandatory. This will be the focus of future research and development activities beyond WAVE experiment and cannot be the subject of the present paper. In fact, the flying-alone IKNOW satellite can just provide a marginal contribution to this task, due to its intrinsic reduced visibility (time-wise) from a ground site. Differently, the second objective can be effectively achieved by means of the capability of a nanosatellite injected in LEO. Therefore, in the present paper we will thoroughly address this topic.

The frequency bands of specific interest are:

- 81-86 GHz for the uplinks;
- 71-76 GHz for the satellite downlinks;

At present, the W band frequency range is an unexplored domain in space missions due to the fact that it represents a "technological border". Regardless, it exists a minimum know-how in this domain, acquired especially for terrestrial military and civilian applications. However, the availability of space qualified devices is rather poor and any foreseen development for space applications might be very costly.

Accordingly, our study was also focused on the implementation of candidate experimental packages using COTS via additional screening tests as appropriate. The adoption of COTS component could be one of the key factors in the successful deployment of W-band nanosatellite technology, nevertheless it might be also a potential risk factor. In fact, low-cost hardware technology is often characterized by non-ideal and non-linear behaviors whose impact on the performance of a W-band communication link has been extensively studied in [12]. Non-linear amplifiers, non-ideal filters, clock generators with unstable frequency and, most all, phase noise introduced by EHF oscillators can involve not-negligible distortions and drifts and, therefore, seriously impair PHY-layer performance. Such kind of impairment factors must be carefully taken into account in payload design. Actually, the performance degradation due to the adoption of hardware components characterized by non-ideal behaviors should be quantified in the link budget as an additional loss of signal-to-noise ratio. Experimental results shown in [12] evidenced a not-negligible TX/RX loss due to hardware impairments equal to 4.25 dB.

The remaining part of the paper is organized as follows. In the next section IKNOW mission will be presented. In Section 3 IKNOW payload features will be faced, focusing our attention on payload design. Moreover, the two experiments that IKNOW satellite will carry on will be detailed. Section 4 will deal with potential impairment factors affecting channel propagation and with hardware non-ideality. Finally, conclusions are drawn in Section 5.

II. IKNOW: A SMALL LEO EXPERIMENTAL MISSION IN W-BAND

The IKNOW mission aims at implementing a low-cost W-band experiment on-board a nanosatellite that will be launched into a LEO orbit to verify the W-band suitability to establish a satellite link between space and Earth and to get a first insight of the operational problems related to the use of this frequencies range. The general objectives of the mission can be divided in two different categories: *(i)* scientific objectives, concerning the W-band satellite channel troposphere attenuation characterization and quality measurements, and *(ii)* technological goals, regarding in-orbit validation of W-band hardware and space qualification methodologies. With regards to the first scientific objective, the IKNOW mission should realize a propagation preliminary channel assessment; currently no W-band troposphere measurements have been conducted and no statistical or empirical models are available. In fact, it is only possible to obtain a preliminary order of attenuation levels using the models validated at lower frequencies (e.g.: ITU ones [13] - [17]). IKNOW should provide the preliminary information that will be helpful for the creation of empirical models or for the validation of physically-based electromagnetic models. For what concerns the second scientific objective, IKNOW mission should realize a database of Bit Error Rate (BER) measurements both for uplink and downlink (or for the complete ground-satellite-ground chain). In such a framework, the payload has to be able to send and receive a modulated W band signal for the realization of a preliminary pre-operative channel assessment. To this aim, a specific modulation (or a restrict set of modulations) will be considered. From BER measurements it will be also possible to acquire some information on propagation impairments that could be useful in the frame of the first mission scientific objective.

In addition to W-band satellite channel measurements, the mission will also give first results on W-band COTS hardware and space qualification methodologies by using the W-band frequencies allocated by ITU for ASI experiments, i.e.: 81-86 GHz for uplink and 71-76 GHz for downlink. In fact, being IKNOW the first satellite mission with a W band payload, making in-orbit test of hardware represents a key issue in order to take advantage of it. Aiming at this, the embarked payload will transmit to ground a rich set of components health/status data in order to perform hardware in-flight test. All these data will be monitored, collected and analyzed on ground stations.

The IKNOW mission scenario is depicted in Fig. 1. The foreseen infrastructure is composed by the following elements:

- Space Segment;
- Ground Segment.

The space segment is represented by the satellite. It can be conceived as the combination of a supporting platform and the payload. Obviously, a demodulation and modulation section could be foreseen, in order to realize uplink channel BER measurements.

In order to meet the mission requirements, the platform is required having the following features:

- three axis stabilization and attitude control;
- room for accommodating a 5-15 kg W-band payload: a nanosatellite in the range of 20-30 kg could be suitable for the mission objectives;
- a DC power-to-payload in the 5 to 25 W range, not necessarily continuously;
- compatibility with multiple launch vehicles and of living in LEOs with different inclinations;
- a nominal lifetime of 2 years.

The ground segment consists of the Ground Stations, the Mission and Satellite Control Center and the Data Acquisition and Processing Centre. Two ground stations are foreseen: a fixed ground terminal located at Spino D'Adda (Milan, Italy) site, used previously in various propagation measurements and equipped to achieve low attenuation levels even in poor channel conditions; a transportable ground terminal mostly located in the area around Rome. The implementation of the mobile ground station increases the complexity of the payload with respect to the antennas, but at the same time it allows a particularly broad collection of propagation measurements in various places and weather conditions, giving the ability to change locations (latitudes). The transportability allows to use high-resolution weather forecasts in order to relocate the station in relation with scientific experimentation measurement requirements (clear sky, light or heavy rain, different clouds types, etc.).

Ground terminals should perform some power measurements in order to carry out a preliminary characterization of the W band channel behavior; furthermore, it will also be mandatory to collect meteorological data and relate them to the power measurement performed at the same time. These measurements should be continuously collected in fixed intervals. The recording of meteorological data must be synchronized with the power measurements recording. The P/L informs the Control Centre of the signal measurements acquisition through the TT&C channel. The IKNOW Satellite Control Centre (SCC) is composed by a payload control station and a platform control station. The payload control station will consist of a computer station which will enable the definition of the satellite mission planning according to the user requests coming from the User Interface. The User Interface is based on a second work-station and it is fully dedicated to the web connection with the scientific mission users. Most of the mission control activities will be performed inside this center, which is also responsible for the preparation of MCMDs (Macro-Commands) and satellite status control. The satellite control station, is a computer station which only transmits and receives telemetries. The function of the control station is monitoring the wealthness of the satellite and tracking the precise position of the satellite through Tracking, Telemetry and Command (TT&C) channel. The TT&C subsystem will operate in the "standard" S frequency band. The same channel is also used for sending the information about the reception on the satellite of the signal transmitted by the ground station. After that, these information are sent from the Control Station to the Data Acquisition Centre.

IKNOW satellite will orbit at an altitude of about 700 km passing over both stations at Spino D'Adda and Rome, whose geographical features are summarized in Table I.

This altitude was chosen for a number of reasons, mainly: the need for reduced power, better incident angle (the complementary of the elevation angle) and longer visibility time.

In order to calculate the access duration from the two ground sites, let us consider one satellite for two different orbital planes with inclination angles of 90° and 50° respectively, a satellite drag coefficient of 2.0, and an area-to-mass ratio of $0.003 m^2/kg$. Satellite Tool Kit (STK) simulator has been employed to perform the aforesaid computation whose results are shown in Fig. 2 and Fig. 3. The graphs reported in these two figures show the orbit followed by the IKNOW satellite for the two considered orbital planes during a one day time interval (10 June 2008 – 11 June 2008).

Although this study is focused on the deployment of a single nanosatellite, a small constellation would provide sensible benefits from reliability, experiment coverage and accessibility, and data collection viewpoints. So, also the multi-satellite option could be considered in order to take advantages from a wider coverage and a higher accessibility time, improving the performance of the planned experiments. In fact, to have a wider coverage would allow to collect data in distributed locations characterized by different meteorological features, which means different propagation conditions. While having higher access time would permit to conduct experiments with longer observation times. This result with the possibility of obtaining statistically reliable and robust models, with no significantly increasing the system costs.

Concerning the orbit choice and in order to keep low the overall project costs, the nanosatellite must fly in piggy-back. Therefore, the destination orbits will most likely depend on the launch vehicle that will carry them. We performed in advance several simulations aimed at assessing the impact on the access to the satellite from ground terminals both in Italy and in selected, representative, sites outside Italy. This was done for both a single satellite and for constellations of two to four nanosatellites injected either in near-polar orbits or in circular orbits with inclination of 40° and 50°. It should be noted that the latter inclination is the minimum enabling satellite visibility from the northern part of Italy.

A summary of key results is reported in Table II for orbit inclinations of 90° and in Table III for inclinations of 40° and 50°, a mean satellite orbital altitude of 700 km, and -for the ground terminal- a minimum elevation above the horizon of 5°. The simulation results confirmed that:

- inclinations below 50° would neither meet the requirements of the national scientific community nor that one of other potential European experimenters;
- inclinations between 50° and 70° would provide a somewhat better daily visibility than near-polar orbits;
- by increasing the number of satellites from 1 to 3, proportional improvements in the daily visibility time are achieved. This is particularly useful in the perspective of the communication experiments;
- the simulations have shown that rising up 3 to 4 satellites the delta-improvement becomes marginal. Thus, in our opinion, a good compromise can be already achieved with a minimum constellation made up of three satellites.

III. IKNOW PAYLOAD FEATURES

After having analyzed the orbital characteristics of the IKNOW mission (this is always the first step in satellite mission design), let us consider in this section the aspects concerning the payload design.

The IKNOW nanosatellite will host on-board a simple payload based on three different configurations. Actually, three payload options in W-band were considered: a simple beacon transmitter/receiver, a modulated beacon transmitter/receiver, and a transparent repeater. With respect to the three options above mentioned, the first one, known as basic configuration, will carry out only propagation experiments. Specifically, the payload will receive from the uplink an un-modulated signal from ground to carry out power measurements and will transmit in the downlink a simple beacon. The second configuration, known as full configuration, will carry out propagation and data transmission experiments. In particular, the payload will perform on uplink both power measurements (related to the envelope of the modulated signal) and BER measurements, and will transmit on downlink both a modulate signal and a beacon. At last, the transparent configuration, is characterized by the presence of a transparent transponder that is realized splitting the incoming W-band signal into two paths, first one devoted to the signal power detection, second one to perform a signal down-conversion and to send the signal into the transmission chain.

Hereafter, more details will be provided on the modulated/un-modulated beacon sections and on the transparent transponder. Although existing components at these frequencies are mainly associated to the MMW (Millimeter-Wave) instrumentation market, the general availability of space qualified devices is rather poor and their development might be very costly. Accordingly, the study was also focused on the implementation of candidate experimental packages using COTS via additional screening tests as appropriate.

The two-way communication experiment has to be carried out using the transparent repeater, the payload will receive the uplink signal (84 GHz), provide only filtering and amplification, and then send back the signal to Earth using the downlink (72 GHz) frequency. The coding-modulation scheme will be chosen based on the data collected through the Aero-WAVE. Moreover, in addition to its use for the propagation experiment, the 81.5 GHz beacon will also be used for telemetry, control, and tracking purposes. The IKNOW payload architecture is shown below in Fig. 4.

A. *W-band Experiments On-Board the Nanosatellite*

Our study has considered three different experiment scenarios, each including a MMW payload installed on a nanosatellite (or in multiple satellites in case of a mini-constellation) and a ground terminal. The three different MMW payloads were:

- an un-modulated beacon operating in the 71-76 GHz frequency band;
- a narrowband modulated beacon, also operating in the 71-76 GHz band (data rate less than 1 Mb/s);
- a transparent repeater to carry out the two-way communication experiments, receiving uplink signals at 81-86 GHz, provides on-board filtering and amplification, to be retransmitted to ground in 71-76 GHz downlink.

The modulated beacon, typically intended for a propagation experiment, has many commonalities with the un-modulated one, but it is more interesting. In fact, a payload still characterized by a reduced complexity can convey more information to ground concerning for example the behavior of the hardware working in the space environment under the form of telemetry signals.

The two-way communication experiment scenario based on a transparent repeater is also described. It introduces several challenges that have to be coped with and cleverly solved. The satellite payload is more complex and challenging than the much simpler modulated beacon, and certainly more costly than the former. But, as contrast, it can significantly increase the experiment throughput for what concerns the feasibility of performing two-way communications in near clear-sky conditions, in agreement with the underlying assumptions about the possible use of the W-band for space-to-ground links [8]. By using a transparent repeater, the overall architecture will be simpler. In this case, the uplink and downlink will be typically designed so that the uplink C/N_0 is about 10 dB or greater than the downlink C/N_0 (otherwise the overall C/N_0 will be significantly degraded also because of the noise power robbing effect). However, it is worth mentioning here that the reduction of RF-power is of crucial importance at MMW frequencies, as the RF power generation on-board is rather difficult and costly [18] [19].

An important aspect, which has been preliminarily addressed in the study, concerns the system frequency coherence of the satellite and ground system segments, taking into account both the various frequency generators instabilities and the quite high Doppler frequencies which, at these frequencies and for LEO satellites, may reach peak values around 2 MHz and peak Doppler rates of 20 kHz/s. Typical plots of the ground terminal to satellite slant range, Doppler and Doppler rate values during one-half of a nanosatellite pass over the ground terminal are shown above in Fig. 5. The data are for a LEO at 700 km altitude and a beacon frequency of 81.5 GHz.

B. *The Propagation Experiment*

The propagation experiment consists in a modulated beacon installed on-board at least one nanosatellite, and at least one receive-only ground terminal. The satellite payload would consist of two-varactor-controlled Gunn oscillators connected, via an Ortho Mode Transducer (OMT) to a center-fed parabolic reflector, whose feed may include a circular polarizer. The two Gunn oscillators, tuned to different center frequencies in the 81-86 GHz band, may be switched on-off independently, implementing a form of redundancy or, when operated simultaneously, enabling assessing the propagation path transmission characteristics in two orthogonal polarizations. The varactor tuning is employed:

- for temperature drift compensation, via on-board stored look up tables derived from on-ground calibration data. This is important since most commercial Gunn oscillators show high sensitivity to temperature changes;

- to implement Gunn modulation by the telemetry data. To this end the telemetry data streams, at few kbps rates, can modulate - using Phase Shift Keying (PSK) - a video sub-carrier sufficiently spaced apart from the carrier. The latter, on its turn, will frequency modulate the Gunn oscillator.

The ground terminal will receive a modulated beacon carrier which is affected by a variable Doppler, plus any uncompensated drift. The “a priori” knowledge of the nanosatellite ephemeredes allows controlling in real-time the Phase Locked Loop (PLL) oscillator shifting the nominal receiver center frequency very close to that one expected from the satellite. This will enable narrowing the PLL acquisition and tracking bandwidth by at least one order of magnitude, and perhaps more, with respect to what would be needed without any compensation.

Assuming to modulate the beacon with a digital telemetry signal in the kbps range, it will be possible to reach a fairly high S/N ratio consistently with the need to achieve a sufficient measurement dynamic range and to properly decode the telemetry signal. A representative link budget is shown in Table IV, where we made the following assumptions:

- a small aperture horn for the satellite antenna, compatible with an open loop, dynamic, beam pointing system;
- ground terminal G/T: 21.5 dBK resulting from the adoption of a 60 cm diameter parabola;
- ground terminal carrier tracking PLL bandwidth of 1 kHz, assuming satellite ephemeredes prediction-based satellite Doppler compensation in value and rate;
- telemetry data rate: 1 kbps PSK modulated onto a sub-carrier, sufficiently far from the carrier (e.g. in the 20 to 70 kHz range). The latter FM modulates the carrier with an optimized modulation index;
- an AGC loop bandwidth of 10 Hz, deemed sufficient to follow path attenuation rates of up to 20 dB/s

The propagation payload block diagram is given in Fig. 6, showing a single horn antenna, fed by two modulated Gunn oscillators working at slightly different frequencies near 82 GHz and radiating in opposite circular polarizations.

The payload includes a short conical horn antenna, provided with an ortho-mode transducer and a circular polarizer connected to two Gunn oscillators acting as modulated transmitters. This assembly is rigidly mounted to an elevation over azimuth motorized micro-pedestal to re-point the beam bore-sight within a cone of 65° half angle aperture, during the ground terminals overpasses. In our study we considered a device developed by IMT company under an ESA contract for space applications [20]. Gunn oscillators at 82 GHz do exist and are commercially available; the horn can be smooth or corrugated and well within the present manufacturing capabilities. The mass is estimated to be around 1.5 kg and the DC power of the payload 10 W with both Gunn oscillators simultaneously active.

C. The Communication Experiment

The communication experiment consists of two alternatives; either a transparent repeater or a regenerative repeater to be installed on-board at least one nanosatellite, and at least one transmit-receive ground terminal. These satellite payloads are definitely more ambitious than the propagation payload previously described, but can still be built using COTS items using certain precautions to better meet the space environment requirements. The objectives on which we focused our attention are the following:

- multimode operation, including a wide-band two-way communication mode and a one-way, narrow-band, beacon mode;
- in wide-band mode, perform clear weather transmission tests at bit rates from 10 Mbps upwards;
- test the effectiveness of on-board data regeneration (demodulation and re-modulation) for W-band satellite communications in case regenerative payload is used;

The proposed payload architecture, to meet these objectives, is based on the following key points:

- a highly directional steerable satellite antenna, e.g. a 100 mm diameter paraboloid mounted on a two axis positioner;
- a payload transmit section with a 200 mW Impatt-amplifier;
- a payload receiver with a 6 dB NF preamplifier;
- in the case of using a regenerative payload, a multi-rate on board demodulator/re-modulator, handling at least 10 and 100 Mbps data rates, selectable on command. Data rates up to 1 Gb/s (and more) are currently under investigation.

The link budgets (Table 5, Table 6) are presented for the case of a 10 Mbps rate regarded here as the reference case at this stage of the experiment. Higher rates can be supported during a smaller portion of the satellite overpass when the slant range is nearing the ground terminal zenith. It is important to note that the link budgets have been made assuming a near-clear-weather situation, in agreement with the proposed operational use of such frequency bands which aims at establishing low-availability two-way data communications services.

The uplink budget shows that, with the assumed parameters, the C/N at the satellite end has a quality that enables to demodulate and regenerate individual data bits. The link budgets also exhibit a reasonable margin for near-clear-sky operation, hence there is no need for channel coding/decoding operations. Nevertheless, other considerations might suggest to further enhancement of the link performance by means of some channel coding technique. In this case, as a baseline, we would not propose on-board decoding, which can be instead performed on ground at the receiver side: however, the satellite base-band processor can be designed to perform decoding functions, if needed, for experimental purposes.

The payload to be used for the two-way communication experiment consists of the following components:

- a steerable high gain antenna of a 100 mm diameter center-fed mini-Cassegrain will provide the needed gain in one sense of circular polarization. The parabola will be mounted on a two axis (elevation over azimuth) micro-positioner; a mini-rotary joint, optimized for the W-band, followed by a short section of flexible coaxial cable will connect the transceiver located inside the satellite to the parabola;
- a RF-aided antenna pointing system. Indeed, the quite narrow beamwidth (about 2.5°) is not compatible with open loop pointing only, because of the rising pointing losses. Accordingly it is proposed to combine the open loop system - whereby the beam bore-sight is coarsely kept pointed towards the ground terminal site - with a RF sensing of the small deviations of the beam bore-sight with respect to the direction of arrival of the RF signal wave-front emitted by the ground terminal. The instantaneous error sensing can be achieved through a suitable mechanical motion of the satellite antenna as a whole;
- the transparent repeater will be basically composed of the following elements (Fig. 8):
    - a 82 GHz band-pass filter followed by a LNA with typically 6 dB NF, to provide filtering and amplification to the uplink signal;
    - a 12 GHz Gunn oscillator to apply the 72 GHz downlink frequency to the received signal;
    - a transmission power of about 200-400 mW will be provided through a set of SSPA Impatt-amplifiers to be applied for the 72 GHz downlink signal.
- the reception and transmission sections will be connected to the antenna using a duplexer to insure isolation between the transmitted and received signals.

Summarizing, initial estimates of the mass and DC power requirements for the communication payload are the following:

- mass: 0.8 kg for the antenna, everything included; and 4.2 kg for the repeater (not redundant);
- DC power: 25 W when operating. Since the operative duty will be very small, part or all of the DC power, needed during a worst case overpass of 10 minutes of duration, may come from a rechargeable battery. The latter will be based on Li-ion technology.

A critical system item concerns the electrical parts selection/qualification approach. Considering the frequency ranges to be used for W-band telecommunications (U/L: 81-86 GHz, D/L: 71-76 GHz), they are not currently employed in the commercial market. Actually, the existing commercial hardware components (COTS) are developed only around 94-96 GHz, frequencies at which radar applications exist. Moreover, considering W-band technology, at present most of the manufacturing companies are from the USA. Therefore, critical issues in terms of security and/or strategic technology constraints could be involved by the purchase of components and devices beyond the Atlantic ocean. Moreover, this approach does not match with ASI objectives that consider as preferential the deployment of European technology in satellite missions. Two basic consequences follow from the above mentioned constraints:

1. The IKNOW payload feasibility can be achieved only overcoming the technological gap represented by the lack of COTS hardware at those frequencies. In fact, it needs to carry out specific developments in terms of components and devices (MMIC-based). Such developments mean both to modify existing W-band hardware (but operating at different frequency) and to develop new components (e.g., a new run of foundry for LNA). In addition, a direct consequence is an increase of the development times.
2. In order to avoid hardware purchasing from US companies, ASI should aim at supporting and funding Italian and European W-band manufacturers through aimed studies and/or specific developments so to create a founding basis on which to face the technological gap and to upgrade European and Italian expertise in the millimetre domain.

IV. ANALYSIS OF THE POTENTIAL IMPAIRMENT FACTORS

Considering the exploitation of unexplored (or scarcely explored) spectrum portions like W-band, a question naturally arises: are we walking in a plain meadow or are we penetrating inside a dangerous jungle with wild beasts attacking us ? In fact, W-band is theoretically almost uncontaminated by interference (as opposite: Ku and Ka band are almost saturated). But, on the other hand, some uncertainties are still to be solved and potential impairment factors should be carefully investigated. To this aim, we can mention and comment some results achieved during past project activities related to W-band, i.e.: DAVID-DCE experiment [4][12] and preliminary feasibility analysis about “gigabit connectivity” in W-band carried out during the phase A of WAVE [11]. Such research work allowed us to focus some potential impairment factors that can theoretically limit the capacity of a W-band satellite link. The practical development of efficient satellite communication systems working in W-band should take into account these impairments in order to arrange the due countermeasures.

A. Atmospheric Attenuations: a Preliminary W-band Link Analysis

A big question mark about W-band is related to the propagation of the radio wave in the atmosphere. Cumbersome distortions due to multipath propagation, usually affecting lower frequency spectrum like L band and S band, are usually not encountered in the millimeter wave domain. Nevertheless, random attenuations due to power absorption by water vapor and oxygen, shadowing, etc. are currently to be investigated. This is the main target of the propagation experiment described above. Results achieved during this experiment will be really precious for the interested scientific and industrial community. In fact, the available data about W-band propagation are very scarce. Industrial actors dealing with customer services are quite worried about the percentage of availability of the W-band satellite service. The propagation experiment should provide a reliable answer to these doubts.

Up to now, we here report some preliminary analysis considering the extension to W-band of propagation models working at lower frequencies. It is possible to obtain supplementary attenuation predictions according to predictive models based on ESA climatologic data banks and ITU recommendations. The prediction methods used in this analysis are [13] – [17], which present a general technique to calculate each individual attenuation contribution at a fixed value of probability percentage of time and to combine them in the total contribution.

The total attenuation A_T (dB) represents the combined effect due to gases (oxygen and water vapor), clouds, rain and troposphere scintillation. Given that the probability level p is fixed:

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

where:

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

and:

$A_G(p) = A_G(1\%)$, and $A_C(p) = A_C(1\%)$ for $(p < 1\%)$

Rain is certainly the dominant phenomenon (for frequencies greater than 10 GHz) for time percentages less than the 1% of the time. Based on the above equation, the first estimation of the additional attenuation is performed by considering the two ground stations of Spino D'Adda and Rome. A support about climatologic characterization of these locations comes from ESA meteorological databases provided by Radio-communication Study Group 3 website. In fact the results accuracy also depends on the availability of reliable meteorological data .

Fig. 8-11 show the obtained results about additional attenuation in the W-band channel.

For 1% of time the total attenuation does not exceed 20 dB, for an elevation angle down to 30° considering both the up and downlink. Decreasing the elevation angle leads to an increasing of the attenuation of several dB.

B. Time/frequency Uncertainties

In the analysis of the impairment factors, a relevant topic is related to time and frequency uncertainties, i.e.: those unexpected synchronization drifts that can compromise the efficiency of data reception. Considering previous works on W-band link analysis [12][21] we can list the following critical points concerning time/frequency synchronization:

- Phase noise;
- Doppler shift;
- Non-ideal pulse shaping;
- Symbol unbalance.

Phase-noise is a considerable performance degradation factor in real-world communication systems. This phenomenon is peculiar to oscillators and related RF devices (up-converters, down-converters, etc.). An ideal oscillator would have localized tones at discrete frequencies (i.e. harmonics), but any corrupting noise would spread these perfect tones, thus resulting in high power levels at neighboring frequencies [22].

Two different kinds of undesired effects are noticed: a distortion of the transmitted signal, and an alteration of the oscillation period named jitter which may involve synchronizations problems on the demodulator side. Phase-noise is not a trivial phenomenon like additive noise. A noisy perturbation $u(t)$ usually brings about, in an oscillator circuit, a phase instability resulting in an unwanted random frequency shift in the generated carrier. A possible modeling of phase-noise, commonly employed in practical applications, has been proposed in [22]. Such a model is based on two assumptions: i) the phase noise is assumed to be asymptotically stationary, and ii) the input perturbation $u(t)$ is assumed to be white thermal noise ($S_u(f)$) is assumed to be constant over f [22]). Under these assumptions, the analysis shown in [22] pointed out that the phase-noise power spectral density (PSD) is proportional to $1/f^2$, i.e.:

$$S_\phi(f) = \lambda f_c^2 / f^2 \qquad (2)$$

λ being a constant measured on the basis of the ratio L of the single-sideband (SSB) phase-noise power to the power in the fundamental (expressed in dBc/Hz), for a certain frequency offset (f_m). This last numerical datum is usually reported in the data sheets of commercial oscillators.

A significant drawback involved by the use of such a model is that low-frequency phase-noise spectral components proportional to $1/f^3$, are completely ignored. For this reason, the model proposed in [22] should be modified, by considering a more generic transfer function $H(f)$ of a noise-coloring block that can be designed on the basis of the measured phase-noise masks. An example of such kind of phase-noise masks is shown in Fig. 12. It is related to the overall phase noise measured at the input of the on-board demodulator at 94 GHz and of the on-ground demodulator at 83.5 GHz in the DAVID-DCE experiment [12].

The effect of phase-noise is to produce a *residual phase jitter* at the output of a generic carrier recovery loop. Such jitter can be expressed as follows [23]:

$$\psi_\phi = \sqrt{2\int_{B_L}^{R_s/2} S_\phi(f)\,df} \qquad (3)$$

where B_L is the carrier loop bandwidth [24], R_s is the symbol rate, and $S_\phi(f)$ is the one-sided PSD, converted from dBc/Hz to rad^2/Hz.

As far as the digital demodulation task is concerned, the aforesaid residual phase jitter critically impacts on symbol decision and, therefore, on system performance in terms of bit-error-rate. Some interesting measurements about residual phase jitter have been reported in Table 7 concerning the application of Trellis-Coded-Modulation (TCM) in order to efficiently implement the "gigabit connectivity" over W-band LEO satellite link [11]. In the first column of the table values are shown of $L(f_m)$ accounting the phase-noise level at the output of an oscillator, in the second column the corresponding values of the phase-noise standard deviation are listed. Note that, as expected, the residual jitter increases as the modulated signal bandwidth increases. Values reported in Table 11 clearly point out phase-noise is a serious problem for M-ary modulations. In fact, a residual jitter ranging from 12° to 20° can be almost lethal in the perspective of a correct symbol estimation.

A possible solution to make easier this task is to adopt a modulation scheme with residual carrier, as proposed for the DAVID-DCE payload [12]. The solution described in [12] relied on the transmission a BPSK Split-Phase Manchester-coded signal. Despite the good results in terms of simple and efficient carrier recovery (a simple 2nd order PLL is employed with satisfactory results in terms of frequency tracking), such a solution presents some weak points in terms of spectral efficiency (equal to 0.5bit/s/Hz) and power efficiency (the presence of the residual carrier in the signal spectrum involves a 3dB-power waste). An alternative carrier recovery scheme robust to phase noise, has been proposed in [21]. Such a scheme is particularly targeted to M-QAM modulations. It combines a Costas loop with a 2nd order PLL in order to estimate carrier frequency by using all symbols belonging to the constellation. No symbol is discarded as it happens in other state-of-the-art M-QAM carrier recovery schemes (see e.g. [25]).

In the context of the IKNOW small mission, issues related to phase noise should be carefully taken into account. The utilization of low phase-noise Gunn oscillators (mentioned in Sect. 3) will allow to reduce the amount of phase noise "at the source". Such a choice will positively impact on the global performance of the data communication system. In fact, the adoption of RF analog hardware characterized by low frequency drifts would allow to design efficient carrier recovery and modulation schemes, using standard HW tools (like, e.g.; PLL, Costas' loop [24], m-th power carrier recovery loop, etc. [24]), therefore avoiding the implementation of sophisticated frequency tracking circuitry. In any case, if we consider the relatively low data rates of IKNOW data communication experiment (lower than 10 Mb/s), the adoption of spectrally efficient modulations like M-PSK and/or M-QAM with complex carrier recovery schemes and/or costly RF hardware does not appear very useful. For this reason, the same PHY-layer solution adopted for DAVID-DCE based on SP-BPSK modulation with Manchester coding of the bitstream might be advisable also for the small mission discussed in this paper. Such a solution is theoretically robust in the presence of high Doppler shift and phase-noise and can be easily implemented by using standard and cheap analog circuitry. Nevertheless, the effectiveness of the carrier recovery using a simple PLL depends on how the "spectrum hole" containing the carrier row is large. This means that an effective carrier recovery can be performed if the data rate is much higher than Doppler frequency. In the DAVID-DCE experiment, such a solution has been demonstrated as very effective [12]. In fact, the maximum Doppler shift was measured in 2.5 MHz, whereas the channel symbol rate for the downlink has been assigned equal to 100 Mb/s. In the case of IKNOW mission, the carrier recovery solution using the PLL without any kind of Doppler measurement could become very critical and even impossible if the considered bit-rate was lower than Doppler shift (it is forecast to equal 2 MHz). In this last case, the initial Doppler measurement is mandatory in order to pilot the local VCO. In such a way, only a reduced Doppler error must be tracked by the PLL that should be able to dynamically adjust the recovered frequency.

To conclude this section, let spend few words about time uncertainties. Two well-known time drifts usually affects the baseband symbol emission: the non-ideal pulse shaping and the symbol unbalance. Non ideal pulse shaping turns on rectangular NRZ pulses with nonzero raising and fall time and raised cosines whose eyes diagram is a bit "squelched". In real applications, it very difficult to obtain "ideal" pulse waveforms, so the presence of some imperfections in the pulse shaping should be tolerate. The resulting Inter-Symbol-Interference (ISI) would be negligible, if good-quality circuitry producing the waveform is adopted. On the other hand, symbol unbalance could be a nasty problem. The unequal rise and fall times of the logic gating function may cause asymmetry in the symbol duration [26][27]. It is usually assumed that symbols at level "+1" are of slightly longer duration than symbols at level "0". This phenomenon can involve an additional noisy jitter of the data clock that can considerably lower the performances of clock synchronizer loops at the receiver as mentioned in [27]. Time uncertainties are not peculiar to W-band environment, like e.g. phase noise. But they are aspects to be carefully considered as well, especially if we are moving towards a "broadband" perspective: meaning very high data rates and therefore increased sensitivity to timing errors.

V. CONCLUSIONS

In this paper, preliminary results of an experimental mission targeted to exploring the feasibility of a satellite connection in W-band is presented and discussed in details. The mission relies on a small LEO satellite (namely IKNOW) and is targeted both at appraising channel propagation conditions (narrowband beacon mode) and at evaluating quality-of-service in real data transmission (wideband two-way communication mode).

The experimental scenario was depicted, considering orbital issues, payload architecture and potential impairment factors to be carefully considered in payload design. The development of small Commercial-Off-The-Shelf based payloads will permit to perform experiments by means of simple and cost effective payloads. The tradeoff is related here to the utilization of hardware components whose characteristics are considerably non-ideal with consequential degradation of the performances due to involved distortions and increased noise. In particular, phase noise added by low-cost high-frequency oscillators can seriously impair carrier recovery if spectrally-efficient modulations without residual carrier are employed for digital transmission. Such a choice will be mandatory if data rates higher than 100 Mb/s are considered in the perspective of the "gigabit connectivity". This is not the case of IKNOW small mission, where maximum data rates of 10 Mb/s has been considered in the two-way communication experiment. For this reason, a modulation solution with residual carrier (like the Split-Phase Manchester-coded BPSK of [12]) could be profitably proposed. But, considering the data rates comparable with a very high Doppler shift typical of LEO satellite connection, there would need of preliminary Doppler estimation and compensation in order to make carrier recovery feasible.

The key features of the satellite propagation and communication experiment payloads, as well as those of the ground terminal, are in principle applicable to other more ambitious experimental missions not only based on nanosatellites.

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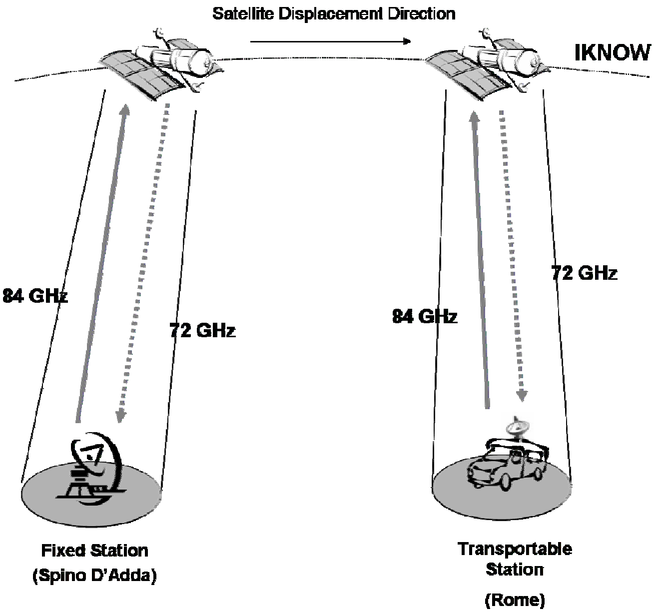

Fig. 1. The IKNOW scenario

Table I
Geographic parameters of the selected locations

Location	**Latitude**	**Longitude**	**Altitude [m]**
Spino d’Adda	45.4° N	9.5° E	84
Rome	41.9° N	12.5° E	32

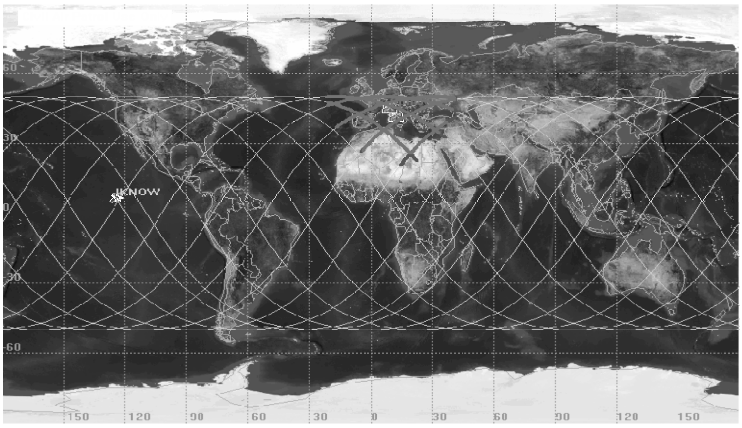

Fig. 2. One day orbit for IKNOW satellite with i=90°

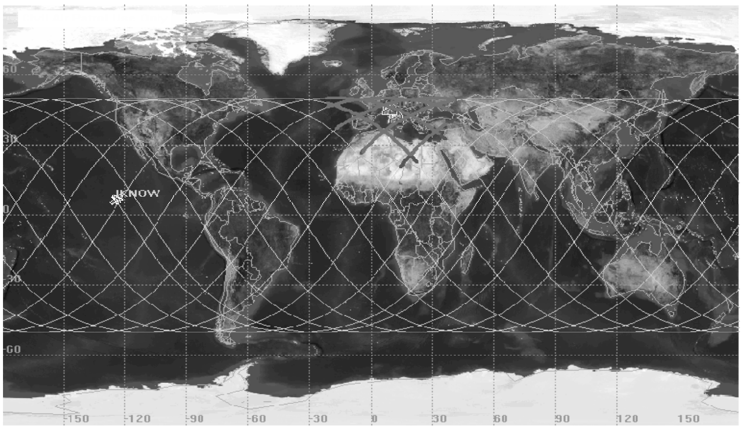

Fig. 3. One day orbit for IKNOW satellite with i=50°

TABLE II
Satellite constellations in near-polar orbits

N° of satellites	orbit parameters	visibility from Rome (min/pass.)
1	i= 90°	5.09
3	i=90°, RAAN: 0-60°-120°	14.64

TABLE III
Satellite constellation in inclined circular orbits

N° of satellites	**orbit parameters**	**visibility from Rome (min/pass.)**
1	i=40°	5.7
3	i=50°, RAAN: 0-120°-240°	18.46

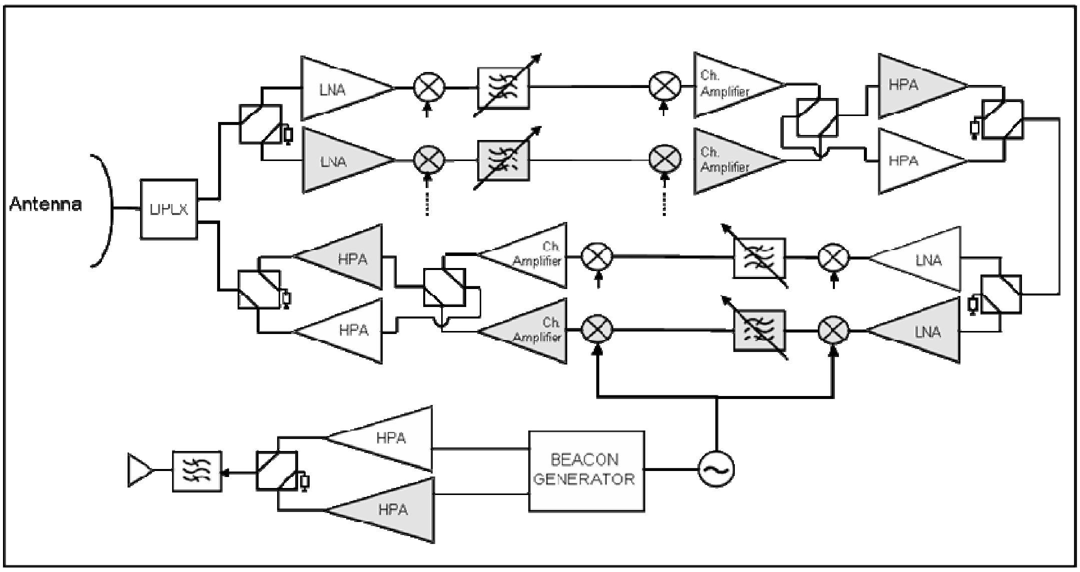

Fig. 4. The IKNOW payload architecture

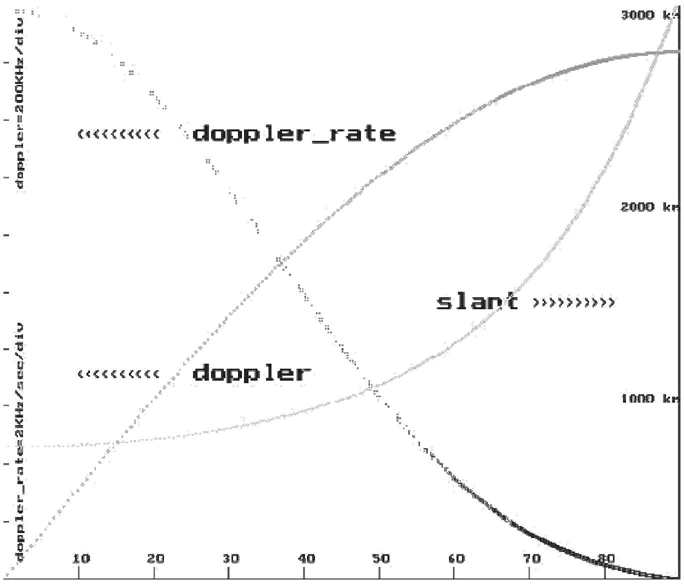

Fig. 5. Slant range, Doppler and Doppler rates during one-half (horizon to zenith) of a satellite overpass in view of a ground terminal

TABLE IV
Propagation experiment link budget

parameter	**value**	**Remark**
sat. TX power	-13 dBW	50 mW Gunn osc.
satellite antenna gain	27 dB	small horn
Pointing losses	-1.5 dB	worst case, open loop pointing
on board losses	-1.5 dB	Ohmic
EIRP	11 dBW	
Path loss, c.w.	-197.5	2100 km slant at 81.5 GHz
additional propagation loss	30 dB	assumed ‘target’ measurement range
Ground G/T	27.5 dB K	0.6 m antenna; 1000 K T_{syst}
On ground losses	-1 dB	
Carrier mod. loss	-3 dB	
Signal mod. loss	- 5.4 dB	
Carrier S/N	5.6 dB	in 1kHz PLL BW
S/N in AGC bandwidth	22.6 dB	20 Hz BW
telemetry signal S/N	7.2 dB	in 250 Hz BW
Telemetry signal decoding gain minus impl. losses	2.5 dB	min. required
min. telemetry signal decoded S/N	9.7 dB	

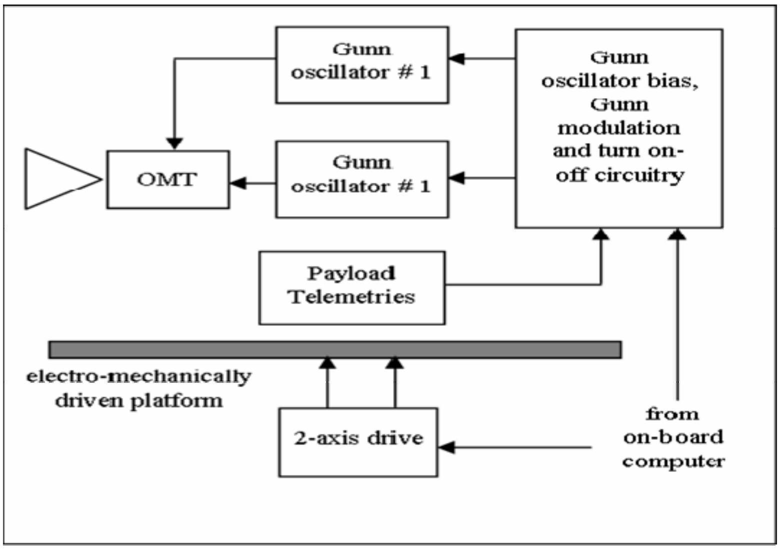

Fig. 6. Propagation experiment block diagram

TABLE V

Downlink budget, regenerative repeater

Parameter	**value**	**Remark**
Sat. Tx. power	-7 dBW	200mW Impatt amplifier
Sat. antenna gain	36	peak gain (100 mm diameter at 82 GHz)
On board losses	-2 dB	Ohmic, pointing
EIRP	27 dBW	-
Path loss, c.w.	-197.5 dB	2100 km slant
atmospheric losses	- 2 dB	near clear weather
Ground antenna gain	57.5 dB	1.2 m diameter parabola.
ground losses	-1.5 dB	Ohmic, pointing
KTB	-130.6 dB K	10 Mbps; 600 K T (cooled LNA)
C/N	15.6 dB	-
Margin to 9 dB	6.6 dB	Uncoded

TABLE VI

Uplink budget, regenerative repeater

Parameter	**value**	**Remark**
Grd TX power	-2.2 dBW	2 x 300 mW Impatt in parallel
Grd antenna gain	56.5 dB	At 72 GHz
On ground losses	-1.5 dB	Ohmic pointing
Grd EIRP	52.8 dBW	
Path loss, c.w.	-196.2 dB	2100 km slant at 72 GHz
atmospheric losses	-2 dB	near clear weather
Sat ant. gain	35 dB	peak gain
onboard losses	-2	Ohmic pointing
KTB	-128.6 dB K	10 Mbps; 1000 K T_{system}
C/N	16.2 dB	
margin to 9 dB	6.6 dB	uncoded

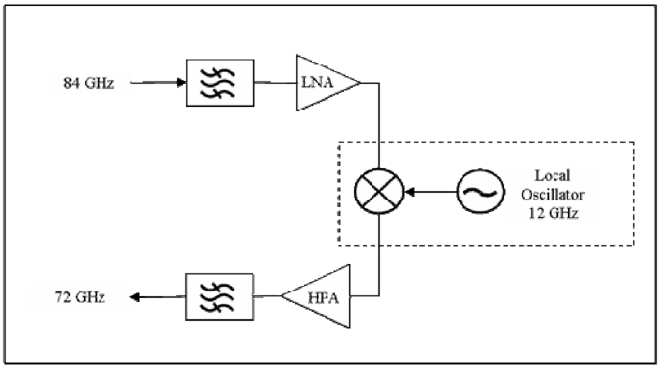

Fig. 7. Communications experiment - transparent payload

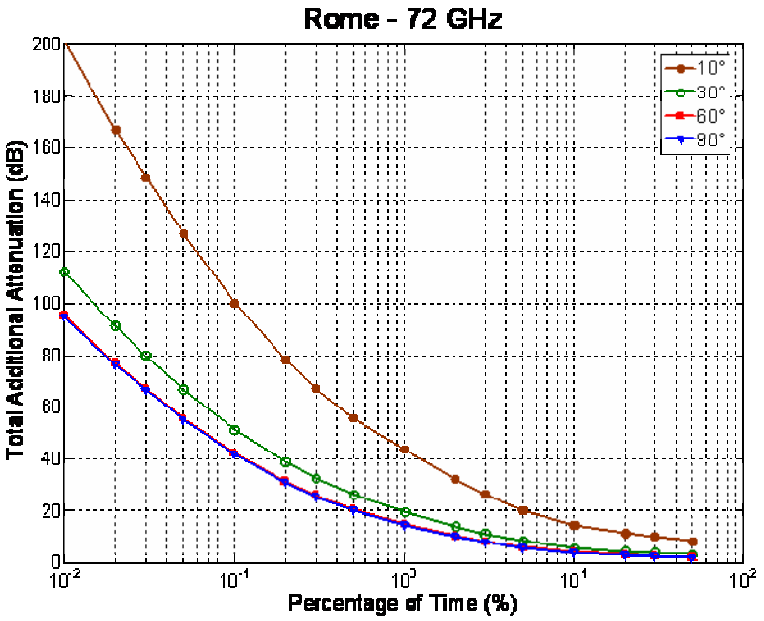

Fig. 8. Downlink total attenuation - Rome

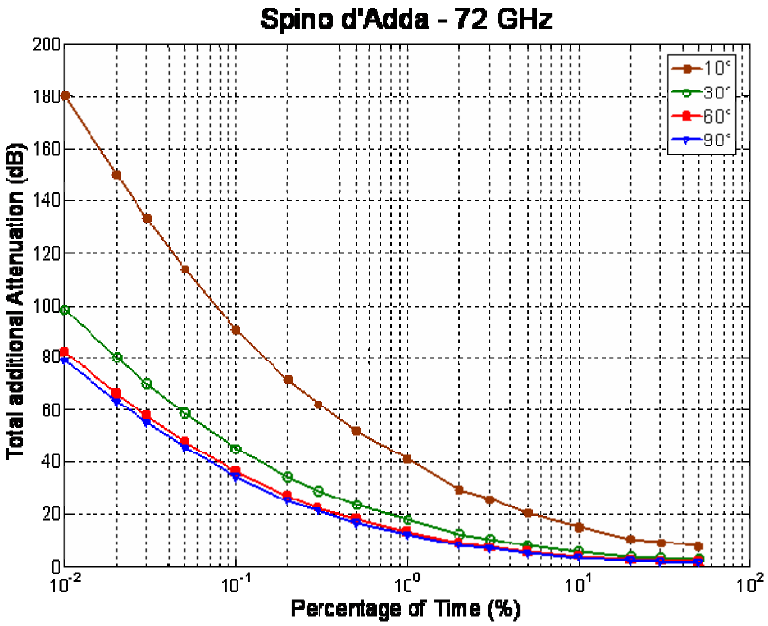

Fig. 9. Downlink total attenuation - Spino d'Adda

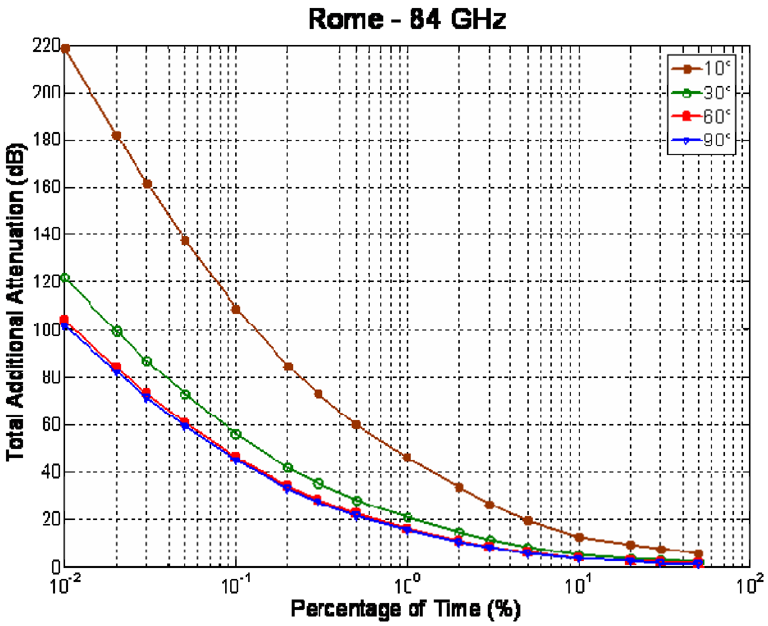

Fig. 10. Uplink total attenuation - Rome

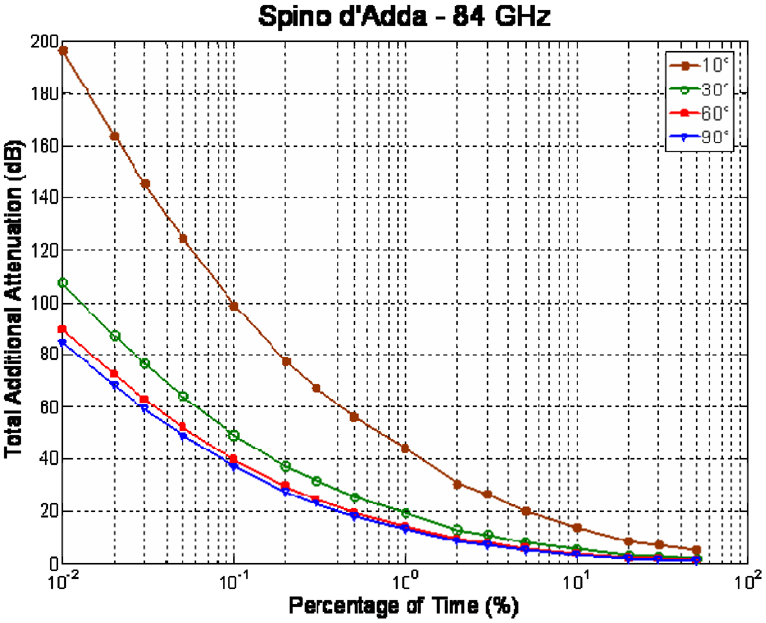

Fig.11. Uplink total attenuation - Spino d'Adda

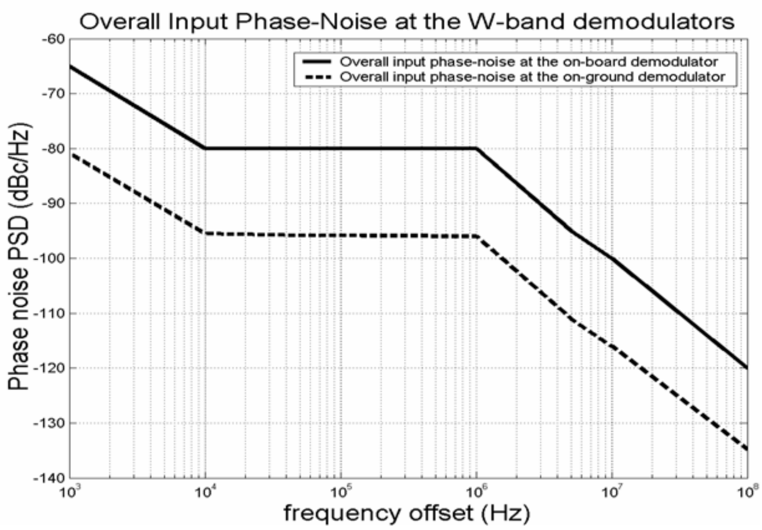

Fig. 12. Phase-noise masks related to the RF level of the DAVID-DCE payload, i.e.: at the input of the on-board demodulator (94 GHz) and on-ground demodulator (83.5 GHz)

TABLE VII
Residual phase jitter in a 1Gb/s W-band LEO connection using TCM

$L(f_m)$	σ_ϕ	$\psi_\phi(8-QAM)$	$\psi_\phi(16-QAM)$	$\psi_\phi(64-QAM)$
-70dBc/Hz	22.85°	19.85	16.21°	12.81
-75dBc/Hz	12.83°	11.16	9.11°	7.21
-80dBc/Hz	7.20°	6.27	5.12°	4.05
-85dBc/Hz	4.05°	3.52	2.88°	2.27