Performance of satellite-to-ground communications link between ARTEMIS and the Optical Ground Station

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ABSTRACT

The European Space Agency has built an optical ground station sited at the Observatorio del Teide operated by the Instituto de Astrofísica de Canarias. This station, equipped with a 1m telescope, has a multipurpose configuration for in-orbit commissioning and checkout of laser communication payloads. Since November 2001, the bidirectional link with satellite ARTEMIS has been established in more than 80 successful sessions. In this paper, we analyze the influence of turbulence parameters on the performance of communications in the bidirectional ground to space laser communication experiments. The link performance observed in the satellite-to-ground channel showed average bit error rates of 10^{-6} over long durations (20 minutes), however in some occasions BER's of at least 10^{-9} -10^{-10} over durations of 5 to 30 minutes were observed. The behavior of the Bit Error Rate measurements performed in different turbulence conditions is characterized.

Keywords: Satellite-to-ground laser communication, ARTEMIS, OGS, Bit Error Rate measurements

1. INTRODUCTION

The progressive overcrowding of the Geostationary Orbit (GEO), and the much demanding capacity of the last generation of telecomm satellites, in terms both of bandwidth and number of channels, implies a certain risk of saturation in the medium term. The implementation of optical communication terminals in satellites offers a possibility of sustained growth. The advantages are clear, on the one hand the appreciable reduction of volume, weight and power consumption of the payloads, on the other the increase of bandwidth, confidentiality and absence of regulatory restrictions as compared to RF systems. The feasibility of Low-Earth-Orbit (LEO) to GEO inter-satellite optical communication has been successfully demonstrated[1]. However there is a fundamental difference between free space optical links and optical links between ground based stations and earth orbiting satellites: the perturbation induced by the atmosphere. Apart from the light extinction, the variation of the index of refraction, linked to thermal and dynamical non-homogeneities in the propagation medium, causes the distortion of the light wave-fronts. As a result the beam divergence is larger than the diffraction limit for apertures larger than a few centimeters. The effect of turbulence is asymmetric in downlinks and uplinks, in any case, the proper characterization of this effect on optical links between ground and satellites is necessary for the practical development of future ground-satellite optical communications.

The Optical Ground Station (OGS) of the European Space Agency (ESA), sited at the Observatorio del Teide (OT) and operated by the Instituto de Astrofísica de Canarias (IAC), has been originally conceived to conduct the In-Orbit Test of the optical payload of ARTEMIS satellite[2], although the design of the station is flexible enough to re-configure it in order to establish links with other satellites. The initial test and commissioning sessions of OPALE, the laser communication terminal (LCT) onboard ARTEMIS, started on November 15th, 2001 (one week before the first inter-satellite link) [3]. The potential of the OGS for establishing links with a variety of satellites is a vantage point to study and characterize laser beam propagation through atmospheric turbulence to GEO, LEO and even deep-space satellites. In the frame of the project "ARTEMIS Laser Link for Atmospheric Turbulence Statistics" (ESA contract AO/1-3930/01/NL/CK), we have carried out an specific campaign of 45 bi-directional links between the OGS and ARTEMIS, with several simultaneous measurement of Cn^2 profiles from a neighbor telescope. Altogether, taking also into account the commissioning and routine phases, the Bit Error Rate (BER) was successfully measured in 57 downlinks and 9 uplinks.

In this paper we present the first analysis of the BER measurements of the above mentioned campaign. The paper is laid as follows in Sect. 2 we describe the OGS-ARTEMIS laser link stressing the features of the communications system. In Sect. 3 we present the BER measurements statistics of the downlink and preliminary results of the uplink; furthermore we analyze the influence of turbulence on the BER performance. Finally, we present in Sect. 4 the main conclusions.

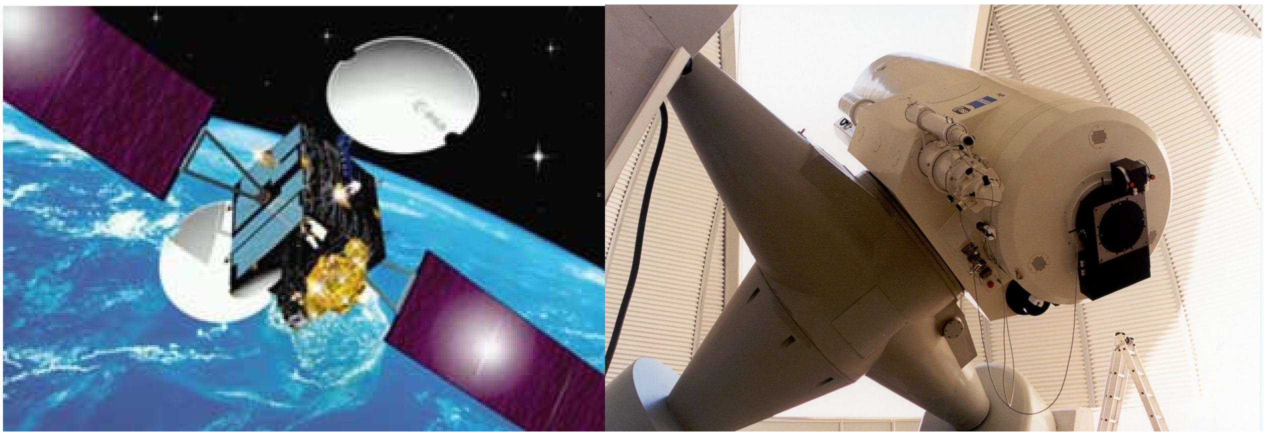

Fig. 1. Left: Artistic view of ARTEMIS satellite (21.5E; 0.0±2.8N; 35787km). Right: The OGS 1m telescope with English Equatorial mounting, sited at the Observatorio del teide (343.4899E; +28.2995N; 2393m). The OGS is equipped with a configurable LCT in the optical bench of the coudé focal plane located in the floor under the dome.

2. A GENERAL OVERVIEW OF THE OGS-ARTEMIS LASER LINK

The optical link between the OGS and ARTEMIS has been thoroughly described elsewhere[3,4,5,6], for the sake of completeness, we show a schematic overview in figure 2. In Table 1, the technical data of both optical terminals are summarized.

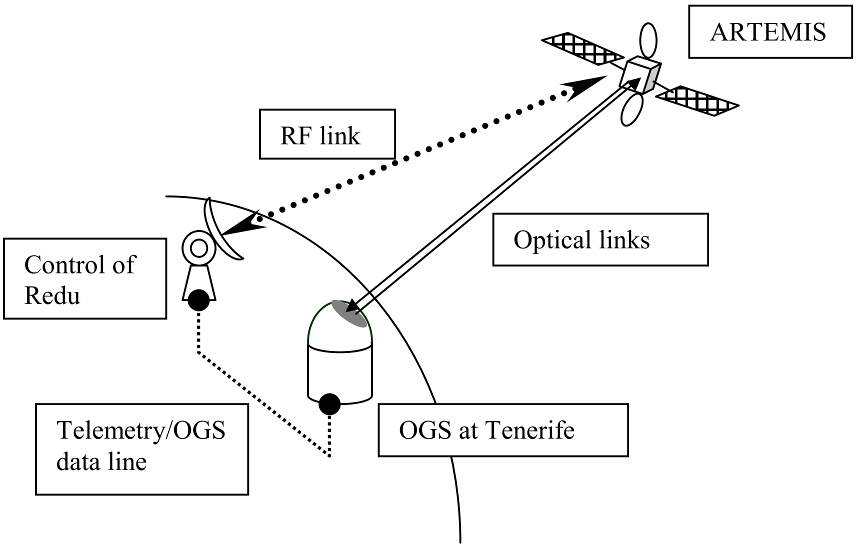

Fig. 2. The ARTEMIS control center at Fucino, Italy (not represented in the sketch) is in charge both of the spacecraft control and of the optical payload (OPALE) operation. ESA control facilities at Redu, Belgium are in charge of the co-ordination and planning of all ARTEMIS payload activities. The RF feeder link in Ka-band 20/30 GHz is performed with a 13.5 meters diameter antenna pointed at ARTEMIS. The OGS at Tenerife, Spain is operated by IAC. The real time telemetry from the satellite and the data collected by the OGS are transmitted via an ISDN line.

	ARTEMIS	OGS
Location and geometry		
Longitude:	21.5° East	16.5101° West
Latitude:	0.0° ±2.81° North (inclination June 04)	28.2995° North
Altitude:	35787 km	2.393 km
Link distance:	38008 ±176 km (June 2004)	
Telescope		
Entrance pupil diameter:	250 mm	1016 mm
Transmitters LCT		
Communication laser:	GaAlAs laser diode, single-mode	Argon laser pumped Ti:Sapphire laser
Laser power out of aperture:	10 mW (average)	300 mW (maximum)
Laser beam diameter ($1/e^2$):	125 mm, one beam	40 mm – 300 mm, four incoherent beams
Communication wavelength:	819 nm nominal (815 nm – 825 nm), measured 818.4 nm on average	847 nm, ARTEMIS filter transmission range 843 nm – 853 nm
Communication polarization:	LHC	LHC
Communication modulation:	2-PPM, 2.048 Mbps (fixed data rate)	NRZ, 49.3724 Mbps (fixed data rate)
Receivers LCT		
Data receiver:	Silicon avalanche photo diode	Silicon avalanche photo diode
Data receiver FOV (diameter):	70 µrad	87.3 µrad

Table 1. The technical data of ARTEMIS and OGS optical systems.

2.1. THE COMMUNICATIONS SUB-SYSTEM OF THE OGS

Once the incoming beam at the OGS telescope reaches the optical bench, it is divided with a beam splitter. The beam is partially steered to the tracking sensor, and partially to the receiving box. The receiving box is equipped with three kind of detectors in order to analyze the physical properties of the incoming signal pertaining the communications performance: A spectrometer, a polarimeter and an Avalanche Photo-Diode (APD) with a BER analyzer. A flip mirror steers the beam to either of the three instruments according to the operator request.

The spectrometer, a modified version of the *Monochromateur* HR 640 de JOBIN YVON, equipped with a diffraction grating from ZEISS, is used for wavelength measurements. The polarimeter, a PEM-90 photoelastic modulator by HINDS Instruments, is used for measuring the power and the state of polarization of the beam. The communications receiver used to measure the Bit Error Counts, the BER and the modulation code, consist of a SF-60 PDH/SDH Error and Jitter analyzer Wandel & Goltermann, which captures the signal from the APD (Table 2) and also generates the modulation signal of the transmitted beam.

APD of the RFE	
Operating Voltage (HV) at 22 ºC	211.5 V
Dark current at 22 ºC	18 nA
Responsivity (mean value with HV)	128 A/W
Noise current	0.1 pA/Sqr(Hz)
Breakdown voltage	219.2 V at 22 ºC; 184.9 V at –20 ºC
Thermistor	5.7 kΩ at 22 ºC; 39.2 kΩ at –20 ºC
Dark count	2100 Cps at 22 ºC; 30 Cps at –20 ºC

Table 2. The technical data of the currently installed APD at the receiving box of the OGS, ARTEMIS receiving box is equipped with a similar APD.

The several instruments of the communications system are controlled by a computer (Communications Sub-system Computer, CSSC), in such a way that the Main Control Computer (MCC) of the OGS sees it as a single instrument, controlling it by GPIB. A block diagram of the CSS of the OGS is shown in figure 3.

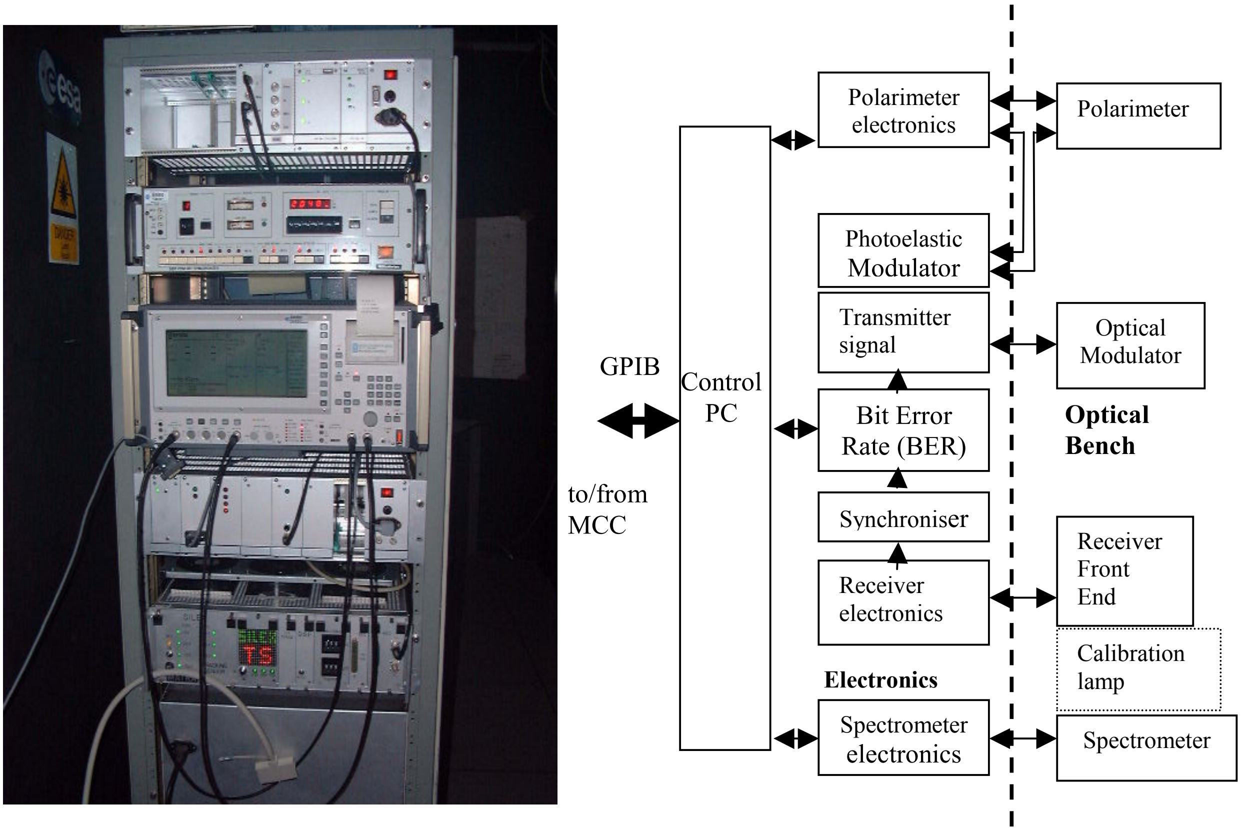

Fig. 3. Left: The electronics rack of the CSS of the OGS. Right: The block diagram of the Communication System of the OGS.

As a transmitter the CSS of OGS can generate a Pseudo Random Bit Sequence (PRBS) from 2^6-1 to 2^{31}-1 with a selectable code and internal clock for bit rates up to 170 Mbps. In the downlink, as a receiver the CSS of OGS can record the BEC and BER in a given gate period with built-in clock recovery for all bit rates.

2.2. THE COMMUNICATIONS SUB-SYSTEM OF ARTEMIS

The communication equipments of ARTEMIS consist of an APD similar to that of the OGS, a 2-PPM modulator, a NRZ to 2-PPM converter, and a laser driver to modulate the intensity of the communications laser. The PRBS transmitted by the LCT of ARTEMIS is provided through Redu feeder link in Ka-band from 27.5 to 30 GHz. The granted BER by the feeder link after differential decoding is better than 10^{-8}. In the uplink, the BER statistics is recorded every second in the telemetry line.

3. COMMUNICATIONS PERFORMANCE: BER MEASUREMENTS AND STATISTICS

The first optical links OGS←→ARTEMIS were performed on November 15th, 2001, when ARTEMIS was still in an equatorial drift orbit after the launching failure[6]. During 2002, ARTEMIS was carried to the geostationary orbit with the help of its ion motors. In 2003 the optical links were resumed. In total 30 experiments has been performed so far, consisting in more than 100 links[6],. The BER was measured in 22 experiments (57 downlinks and 9 uplinks). In table 3 a summary of the communication experiments is presented (propagation experiments are not considered in this table).

Date:	UTC start times of link sessions	Comments
10 Dec. 2001	18:30, **19:30**, 20:30, **21:30, 22:30**	**OPALE commissioning phase:** Verification of OPALE nominal performance before ARTEMIS orbit-raising maneuver started
8 May 2003	**21:00**	**OGS verification phase:** Return to nominal operations
6 May 2003	**21:00**, 22:15	
22 May 2003	**20:30, 21:45, 23:00**	**ARTEMIS Laser Link for Atmospheric Turbulence Statistics:** Tests performed by changing the number of OGS transmit beams and OGS beam divergence for beam propagation analysis. In some experiments simultaneous measurements of C_n^2 profile were carried out with a Scintillation Detection and Ranging instrument.
23 May 2003	**17:00, 18:30**, 21:00	
24 May 2003	**17:00**, 18:30, 21:00	
05 June 2003	**15:30, 16:30, 17:30, 18:30**	
06 June 2003	**20:30, 21:30, 22:30, 23:30**	
10 June 2003	**20:30, 21:30, 22:30, 23:30**	
21 July 2003	**21:00, 22:05, 23:10,** 23:30	
22 July 2003	**21:00**, 22:05, 23:10, 00:15	
23 July 2003	21:00, **22:05**, 23:10, **00:15**	
24 July 2003	**21:00, 22:05, 23:10, 00:15**	
06 Aug. 2003	**21:00, 22:10, 23:20, 00:30**	
07 Aug. 2003	**21:00, 22:10, 23:20**, 00:30	
09 Sep. 2003	20:10, **21:10, 23:30, 00:30**	**LUCE compatibility verification campaign:** Experiments performed to test the compatibility of the engineering model of the LUCE laser communication terminal with OPALE[8].
10 Sep. 2003	**20:10**, 21:10, 23:30, **00:30**	
13 Sep. 2003	**20:10**, 21:10, **23:30**, 00:30	
15 Sep. 2003	**20:10**, 21:10, **23:30**, 00:30	
16 Sep. 2003	**20:10, 21:10, 23:30**, 00:30	
21 Apr. 2004	**21:00, 22:00, 23:00**	**Routine testing phase:** Variation of transmit laser wavelength
26 May 2004	18:30, **20:00, 21:30**	

Table 3. Summary of laser link communications experiments OGS-ARTEMIS where the BER was measured at least in one session. The BER was measured in 57 downlinks of a total of 80 (start time of the link marked in bold face). The BER was measured in 9 uplinks (start time of the link underlined). The shadowed experiments correspond to the ARTEMIS campaign for the study of turbulence which will be specifically analysed in Sect. 3.3.

3.1. THE BER MEASUREMENTS IN THE DOWNLINK

In the downlink, the BER has been measured in a total number of 57 links with durations ranging from 5 to 35 minutes. This corresponds to an elapsed link time of approximately 20 hours, with a mean link duration of 20 minutes. The BER analyzer was operated with zero offset setting the detection threshold at half the signal value. The test pattern was PRBS $2^{15}-1$, and the rate fixed at 2,048 Mbps. The BER was measured with different gate periods ranging from 5 to 40 seconds in order to achieve an acceptable a confidence level in the accuracy of the measurements. There is a 1.7 seconds gap between consecutive measurements, this allows safely grouping the measurements in order to increase the confidence level of the BER determination. The error free level is established at 10^{-8}, however it is clear that the BER measured was better than this value in several links.

In Tables 4 and 5, we present the summary of the BER measurements recorded in all links. The worst values (BER>10^{-4}) were registered in the campaign of December 10th, 2001 before ARTEMIS reached geostationary orbit, with humidity and wind speed over limits. The best values (BER≈10^{-10}) were measured in summer time. The average BER measured in the downlink amounts to 9.838 10^{-7} (figure 4). The maximum variation of the BER measured within a session is in average a factor of 6.5, in extreme cases a variations of nearly a factor of 20 are observed.

Link date	Gate period	Maximum BER in gate period	Minimum BER in gate period	Average BER in gate period	Link duration [s]
10/12/01-1	5	4,672E-03	4,785E-06	2,065E-04	636
10/12/01-2	5	8,618E-04	5,264E-05	1,905E-04	282

10/12/01-3	5	8,016E-04	7,021E-05	2,426E-04	203
06/05/03-1a	5	3,906E-07	<9,765E-08	6,006E-08	443
06/05/03-1b	15	1,950E-07	6,510E-08	1,106E-07	82
06/05/03-1c	20	1,470E-07	4,880E-08	8,153E-08	64
08/05/03-1	20	6,982E-06	2,930E-07	7,381E-07	563
22/05/03-1	20	2,197E-07	2,441E-08	1,188E-07	803
22/05/03-2	20	2,685E-07	<2,441E-08	6,524E-08	1325
22/05/03-3	20	5,127E-07	<2,441E-08	1,491E-07	1630
23/05/03-1	20	2,041E-05	1,570E-05	1,733E-05	868
23/05/03-2	20	4,651E-05	2,266E-05	3,347E-05	1608
24/05/03-1	20	2,632E-05	4,175E-06	7,401E-06	1499
05/06/03-1	20	8,789E-07	2,930E-07	5,742E-07	1630
05/06/03-2	20	1,001E-06	3,906E-07	6,892E-07	1522
05/06/03-3	20	1,538E-06	6,592E-07	9,723E-07	1630
05/06/03-4	20	7,813E-07	2,197E-07	4,183E-07	1630
06/06/03-1	20	6,104E-07	1,221E-07	3,580E-07	1543
06/06/03-2	20	8,301E-07	1,465E-07	4,449E-07	1651
06/06/03-3	20	9,766E-07	3,174E-07	5,743E-07	455
06/06/03-4	20	2,026E-06	1,148E-06	1,567E-06	1368
10/06/03-1	20	9,692E-06	<2,441E-08	2,945E-06	1694
10/06/03-2	20	4,394E-07	1,221E-07	2,408E-07	651
10/06/03-3	20	9,888E-06	1,465E-07	1,351E-06	1651
10/06/03-4	20	1,255E-05	2,930E-07	1,920E-06	1673
21/07/03-1a	20	1,953E-07	2,441E-08	1,106E-07	368
21/07/03-1b	30	2,604E-07	3,255E-08	1,187E-07	1522
21/07/03-2	30	5,176E-06	4,883E-08	9,900E-07	1967
21/07/03-3	30	7,650E-07	7,487E-07	7,569E-07	62
22/07/03-1	30	7,389E-06	4,883E-08	8,878E-07	1680
23/07/03–2a	30	<1,627E-08	<1,627E-08	<1,627E-08	125
23/07/03–2b	40	<1,221E-08	<1,221E-08	<1,221E-08	415
23/07/03–2c	20	2,441E-08	2,441E-08	1,526E-09	1390
23/07/03–4	30	4,883E-08	<1.627E-08	1,033E-09	1997
24/07/03–1a	30	1,479E-05	3,320E-06	8,608E-06	475
24/07/03–1b	30	4,622E-06	3,092E-07	1,179E-06	1205
24/07/03–2	30	1,312E-05	2,116E-07	6,380E-06	1872
24/07/03–3	30	1,447E-05	7,324E-07	4,126E-06	1903
24/07/03–4	30	2,502E-05	2,149E-06	1,419E-05	1680
06/08/03–1	30	2,085E-05	6,673E-07	7,537E-06	2220
06/08/03–2	30	3,799E-05	8,464E-07	1,665E-05	1681
06/08/03–3	30	1,445E-05	6,738E-06	9,633E-06	760
06/08/03–4	30	4,141E-05	1,204E-06	1,423E-05	2220
07/08/03–1	30	1,483E-05	1,302E-07	5,778E-06	2189
07/08/03–2a	30	3,623E-05	5,371E-07	1,429E-05	1871
07/08/03–2b	30	8,496E-06	2,555E-06	4,419E-06	316
07/08/03–3a	30	3,011E-06	1,627E-06	2,275E-06	506
07/08/03–3b	30	1,986E-05	1,188E-06	7,806E-06	411
21/04/04–1	30	7,650E-07	3,255E-08	2,368E-07	982
21/04/04–2	30	2,116E-07	<1,628E-08	3,526E-08	1140
21/04/04–3	30	6,510E-08	<1,628E-08	1,085E-08	1140
26/05/04–2	20	7,324E-08	<2,441E-08	2,044E-08	944
26/05/04–3	20	5,200E-06	<2,441E-08	1,923E-07	673
09/09/03–2	20	4,102E-05	1,514E-06	9,289E-06	1151
09/09/03–3	20	5,054E-05	2,222E-06	1,260E-05	1151
09/09/03–4	20	6,396E-05	6,299E-06	3,490E-05	1151
10/09/03–1	20	7,690E-06	2,173E-06	3,770E-06	304

10/09/03–4	20	3,613E-05	3,223E-06	1,736E-05	1107
13/09/03–1	20	1,406E-05	4,395E-07	2,717E-06	1151
13/09/03–3	20	3,613E-06	<2,441E-08	9,422E-07	956
15/09/03–1	20	2,100E-06	<2,441E-08	7,663E-07	781
15/09/03–3	20	2,368E-06	<2,441E-08	6,335E-07	1303
16/09/03–1	20	<2,441E-08	<2,441E-08	<2,441E-08	1151
16/09/03–2	20	1,196E-06	<2,441E-08	4,554E-07	934
16/09/03–3	20	1,196E-06	<2,441E-08	2,840E-07	1129

Table 4. Summary of BER measurements in downlinks.

Link date	**MeasuredBER in whole link**	**Best measured BER**	**Duration of best BER**	**Accuracy [%] at a confidence level of**		**BER estimation for error-free sequences**		**Comments and remarks**
				3σ	**1σ**	**1σ**	**3σ**	
10/12/01-1	2,066E-04	4,785E-06	5	0,6	0,2			Fogg and wind
10/12/01-2	1,906E-04	5,264E-05	5	1,1	0,3			Fogg and wind
10/12/01-3	2,423E-04	7,021E-05	5	1,0	0,3			Fogg and wind
06/05/03-1a	5,981E-08	6,180E-09	119	41,4	13,8	2,135E-09	1,100E-08	114 seconds error free
06/05/03-1b	1,038E-07	6,510E-08	15	69,8	23,3			
06/05/03-1c	8,092E-08	4,880E-08	20	92,4	30,8			
08/05/03-1	7,195E-07	7,381E-07	20	10,4	3,5			
22/05/03-1	1,157E-08	2,441E-08	20	21,8	7,3			
22/05/03-2	6,347E-07	1,204E-08	42	22,9	7,6	1,106E-08	5,701E-08	22 seconds error free
22/05/03-3	1,490E-07	<2,441E-08	20	47,8	15,9	1,217E-08	6,271E-08	20 seconds error free
23/05/03-1	1,733E-05	1,570E-05	20	1,7	0,6			
23/05/03-2	3,348E-05	2,266E-05	20	0,9	0,3			
24/05/03-1	7,391E-06	4,175E-06	20	2,0	0,7			
05/06/03-1	5,743E-07	2,930E-07	20	2,3	6,9			
05/06/03-2	6,891E-07	3,906E-07	20	6,5	2,2			
05/06/03-3	9,723E-07	6,592E-07	20	5,3	1,8			
05/06/03-4	4,182E-07	2,197E-07	20	8,0	2,7			
06/06/03-1	3,425E-07	1,221E-07	20	9,1	3,0			
06/06/03-2	4,449E-07	1,465E-07	20	7,7	2,6			
06/06/03-3	5,733E-07	3,174E-07	20	13,0	4,3			
06/06/03-4	1,526E-06	1,148E-06	20	4,6	1,5			
10/06/03-1	2,948E-06	1,681E-08	64	3,0	1,0	5,532E-09	2,850E-08	44 seconds error free
10/06/03-2	2,398E-07	1,221E-07	20	16,8	5,6			
10/06/03-3	1,348E-06	1,465E-07	20	4,4	1,5			
10/06/03-4	1,916E-06	2,930E-07	20	3,7	1,2			
21/07/03-1a	1,104E-07	2,441E-08	20	32,9	11,0			
21/07/03-1b	1,187E-07	3,255E-08	30	15,6	5,2			
21/07/03-2	9,884E-07	4,883E-08	30	4,8	1,6			
21/07/03-3	7,569E-07	7,487E-07	30	30,6	10,2			
22/07/03-1	8,849E-07	4,883E-08	30	5,4	1,8			
23/07/03–2a	<4,001E-09	<4,001E-09	125	——	——	1,947E-09	1,003E-08	125 seconds error free
23/07/03–2b	<1,403E-09	<1,403E-09	415	——	——	5,866E-10	3,022E-09	415 seconds error free
23/07/03–2c	1,488E-09	1,161E-09	433	145,8	48,6	5,894E-10	3,037E-09	413 seconds error free
23/07/03–4	1,033E-09	2,596E-10	1934	145,9	48,6	1,278E-10	6,587E-10	1904 secs. error free
24/07/03–1a	8,608E-06	3,320E-06	30	3,3	1,1			
24/07/03–1b	1,176E-06	3,092E-07	30	5,6	1,9			
24/07/03–2	6,385E-06	2,116E-07	30	1,9	0,6			
24/07/03–3	4,119E-06	7,324E-07	30	2,4	0,8			
24/07/03–4	1,419E-05	2,149E-06	30	1,4	0,5			
06/08/03–1	7,538E-06	6,673E-07	30	1,6	0,5			
06/08/03–2	1,668E-05	8,464E-07	30	1,2	0,4			

06/08/03–3	9,631E-06	6,738E-06	30	2,5	0,8			
06/08/03–4	1,422E-05	1,204E-06	30	1,2	0,4			
07/08/03–1	5,782E-06	1,302E-07	30	1,9	0,6			
07/08/03–2a	1,855E-05	5,371E-07	30	1,3	0,5			
07/08/03–2b	4,412E-06	2,555E-06	30	5,6	1,9			
07/08/03–3a	2,275E-06	1,627E-06	30	6,2	2,1			
07/08/03–3b	7,796E-06	1,188E-06	30	3,7	1,2			
21/04/04–1	2,360E-07	3,255E-08	30	13,8	4,6			
21/04/04–2	3,522E-08	1,152E-08	93	33,1	11,0	3,864E-09	1,991E-08	63 seconds error free
21/04/04–3	1,059E-08	1,992E-09	252	60,3	20,1	1,096E-09	5,650E-09	222 seconds error free
26/05/04–2	2,045E-08	4,763E-09	117	48,0	16,0	2,510E-09	1,293E-08	97 seconds error free
26/05/04–3	1,875E-07	7,914E-09	63	18,4	6,1	5,661E-09	2,917E-08	43 seconds error free
09/09/03–2	9,270E-06	1,514E-06	20	2,0	0,7			
09/09/03–3	1,257E-05	2,222E-06	20	1,7	0,6			
09/09/03–4	3,492E-05	6,299E-06	20	1,1	0,4			
10/09/03–1	3,764E-06	2,173E-06	20	6,1	2,1			
10/09/03–4	1,736E-05	3,223E-06	20	1,5	0,5			
13/09/03–1	2,709E-06	4,395E-07	20	3,8	1,3			
13/09/03–3	9,423E-07	2,441E-08	42	7,0	2,3	1,106E-08	5,701E-08	22 seconds error free
15/09/03–1	7,660E-07	4,959E-09	107	8,6	2,9	2,798E-09	1,442E-08	87 seconds error free
15/09/03–3	6,329E-07	1,307E-09	389	7,3	2,4	6,597E-10	3,399E-09	369 seconds error free
16/09/03–1	<4,612e-10	<4,612E-10	1151	——	——	2,115E-10	1,090E-09	1151 secs. error free
16/09/03–2	4,554E-07	3,957E-09	129	10,2	3,4	2,233E-09	1,151E-08	109 seconds error free
16/09/03–3	2,837E-07	1,122E-09	455	11,7	3,9	5,596E-10	2,883E-09	435 seconds error free

Table 5. Summary of BER measurements in downlinks.

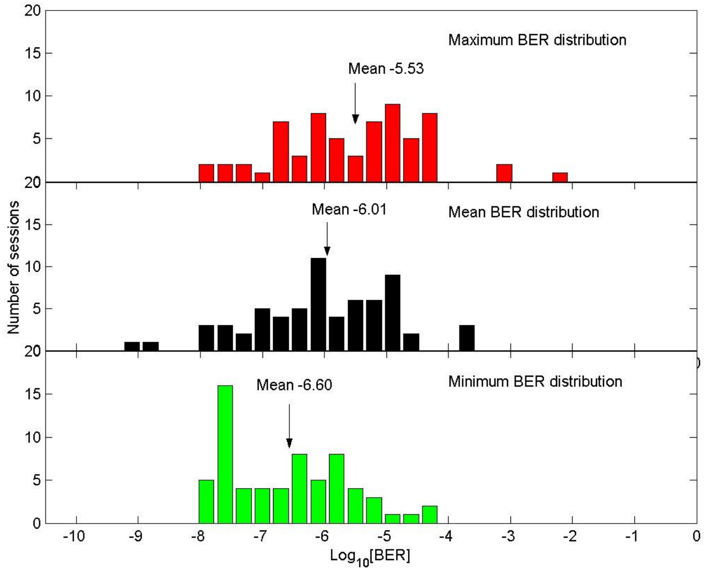

Fig. 4. Distribution of BER measurements. Top: Maximum BER measured in the adopted gate period. Center: BER measured by considering the whole link. Bottom: Minimum BER period measured in the adopted gate period. Notice that there are points with mean BER lower than Minimum BER, these correspond to error free links.

3.2. THE BER MEASUREMENTS IN THE UPLINK

In the uplink, so far the BER has been measured in a total number of 9 links (June 6th and 10th, 2003, September 15th, 2003), corresponding to an elapsed time of approximately 4 hours. The low number of BER measurements as compared to those performed in the downlink is due to the low performance of the modulator for high power laser. In the uplink the code is NRZ, the test pattern PRBS 2^{15}–1, and the rate fixed at 49,3724 Mbps. The BEC was measured every second. The best BER values were in the order of 10^{-5}–10^{-6}, but most of the time BER>10^{-3}. In figure 5, we show an example of the measurements.

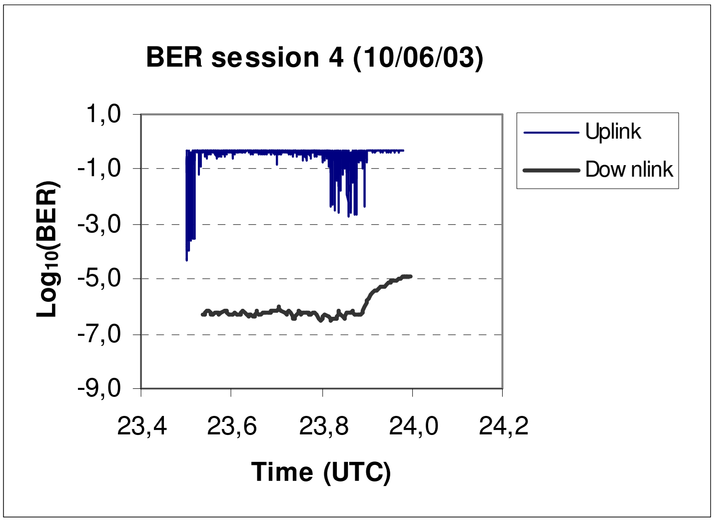

Fig. 5. BER measurements in the 4th link of June 10th, 2003.

It is worthy noticing that the BER analyzer of ARTEMIS could hardly lock onto the signal in the 9 sessions performed in the present experiment. Furthermore, differences with BER simultaneously measured in the downlink range from 2 to 4 orders of magnitude, and in any case never dropped below 10^{-6}. The effect of turbulence is expected to be stronger in the uplink, however it is almost clear that the atmospheric turbulence cannot be blame alone for the low performance observed. The high optical losses in the optical bench of the OGS due to the wide capabilities of the ground terminal demands the use of a 6 W titanium:Sapphire laser which implies the use of a piezo-elastic modulator. This scheme is not clean enough, the output signal did not yield satisfactory enough eye patterns. Therefore the analysis of the uplink performance will be deferred until an optimization in the quality of the modulation of the OGS laser beam.

3.3. THE INFLUENCE OF TURBULENCE ON DOWNLINK COMMUNICATIONS PERFORMANCE

The scintillation indices and fade/surge statistics were determined from the irradiance fluctuations recorded with a four quadrants (4QD) detector at the receiving box of the optical bench of the OGS at 1 kHz.

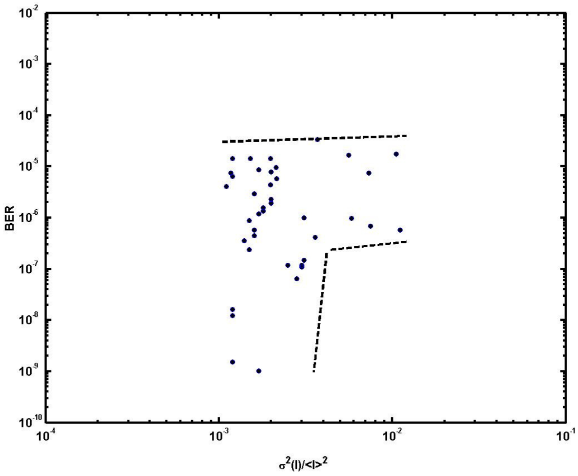

Fig. 6. BER measurements against scintillation index. Lines are marked only for analysis purposes.

The scintillation indices (σ_I) measured range from 0.001 to 0.01, these values are within the theoretical predictions for an averaging aperture of 1 meter[7]. In figure 6, we show the measured BER versus scintillation index. It is worthy noticing that the best values of BER (10^{-9}) are only measured when $\sigma_I < 0.004$, although in this case it is also possible to get high error rates (10^{-5}). However when $\sigma_I > 0.004$ the BER never drops below $5 \cdot 10^{-7}$. A similar behavior is found when we compare BER with the probability and mean duration of fade/surge at 0.5 dB (figures 7-8). In this case, the lower boundary of BER decreases as the probability or duration of fade diminishes, the upper boundary is more or less stable.

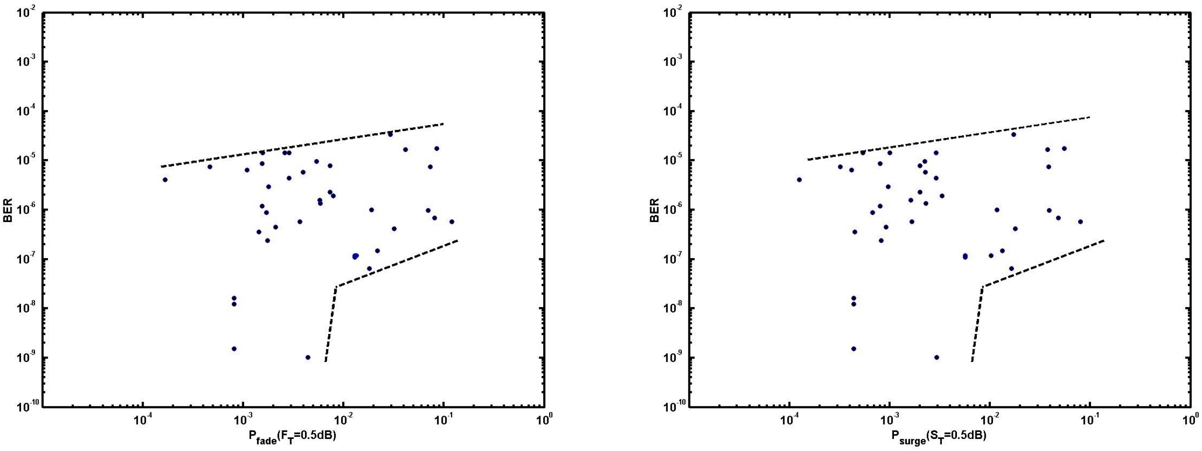

Fig. 7. Left: BER measurements against probability of fade at a level of 0.5 dB. Right: BER measurements against probability of surge at a level of 0.5 dB. Lines are marked only for analysis purposes.

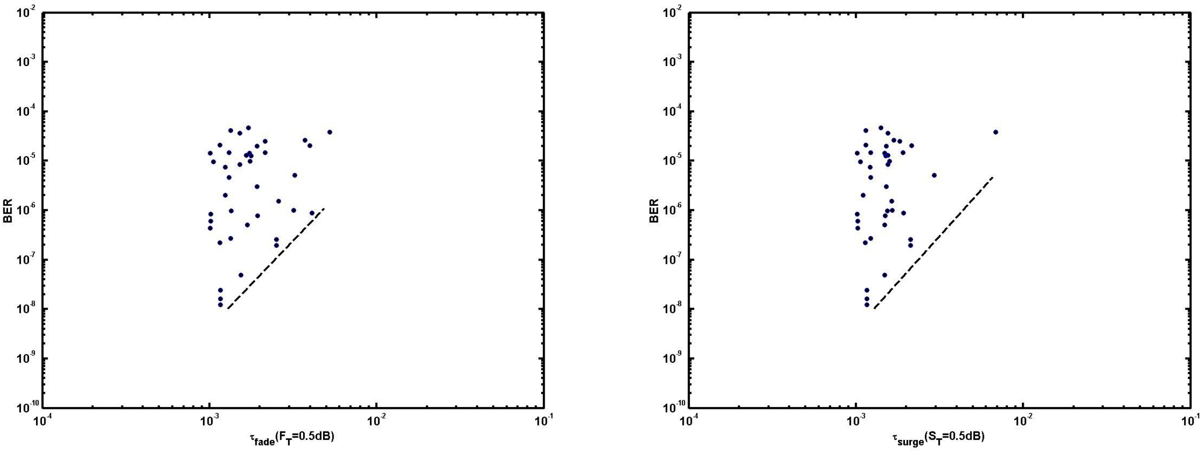

Fig. 8. Left: BER measurements against mean duration of fade at a level of 0.5 dB. Left: BER measurements against mean duration of surge (right) at a level of 0.5 dB. Lines are marked only for analysis purposes.

In some links the profile of C_n^2 was measured by means of a Scintillation Detection and Ranging device (SCIDAR). The features of atmospheric turbulence are usually described by means of the moments of C_n^2 distribution, calculated as

$$\mu_m = \int_0^\infty dz\; C_n^2(z)\; z^m$$

where z is the height above the sea level. In particular, the zero moment (μ_0) is related with "seeing" and five over three moment ($\mu_{3/5}$) is directly related with the isoplanatic angle. From a practical point of view "seeing" is proportional to turbulence in low layers and isoplanatic angle to turbulence in high layers.

During the link, the position of the residual errors of the centroid of the spot in the 4QD detector was recorded at 1 kHz. In principle, these residual errors are related to the "seeing", being the error smaller the fainter the turbulence in low layers. In the present preliminary analysis, we have considered this parameter instead of the “seeing” determined from C_n^2 profile in order to avoid the bias of dome turbulence. In figure 9 (left), we show the BER measurements versus residual errors. It is worthy noticing that BER’s below 10^{-7} are only measured when the residual errors are minimum (best “seeing” values), but otherwise no correlation is found between BER and residual errors.

The correlation of BER with isoplanatic angle determined from C_n^2 profile is shown in figure 9 (right). The result is somehow paradoxical, since the best BER’s are measured with the smaller isoplanatic angles associated to stronger turbulence in high layers, unfortunately for most of the sessions the measurements of isoplanatic angle are lacking.

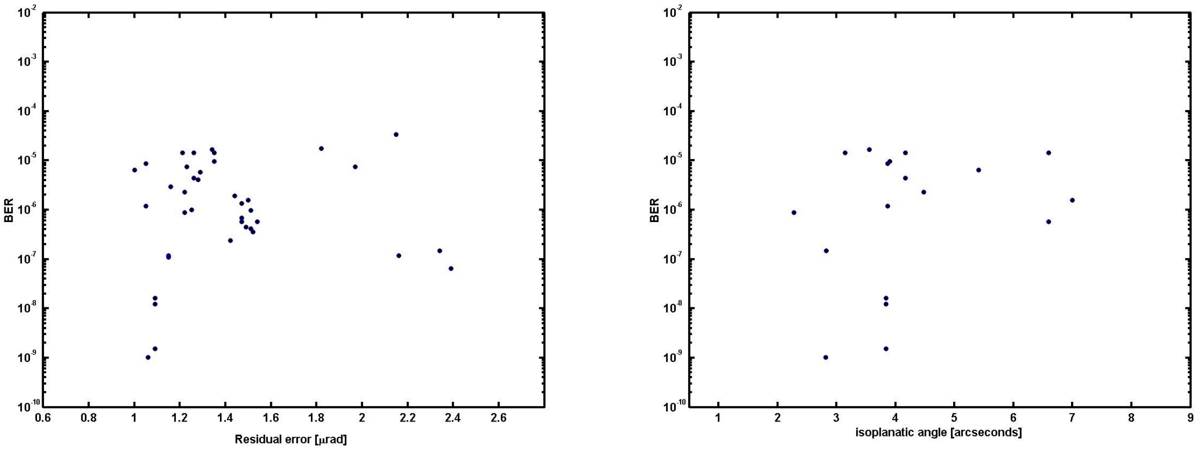

Fig. 9. Left: BER measurements against the module of residual errors of the control loop. Right: BER measurements against isoplanatic angle derived from SCIDAR measurements at a neighbor telescope (right).

Some vertical wind profiles were obtained from balloon surveys performed daily (at noon and midnight) by the Spanish Meteorological Institute. From these profiles, we derived the wind velocity ($\mathbf{v_0}$) to be used in order to apply the Taylor hypothesis with theoretical models. We show in figure 10 (left) the relation of BER with wind velocity. As in the case of isoplanatic angle, there seems to be an anti-correlation of BER with $\mathbf{v_0}$. Incidentally, it has to be remarked that a strong correlation of $\mathbf{v_0}$ with the wind speed at 200 mb (corresponding to the approximate height of the tropopause at the OGS latitude) has been found[9]. We show in figure 10 (right), three examples of C_n^2 profiles measured during the experimental campaign. It can be appreciated the existence of multiple turbulence layers with very different structure.

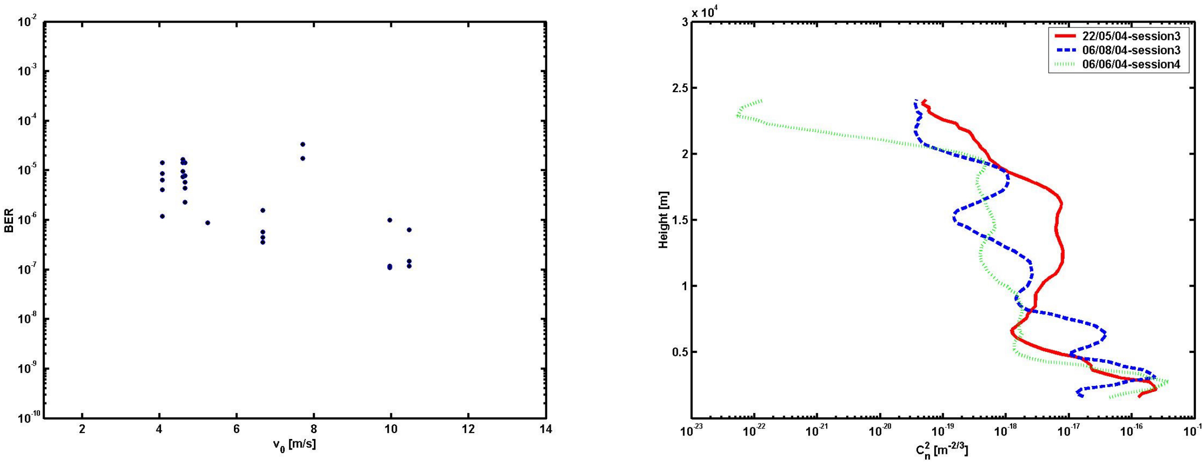

Fig. 10. Left: BER measurements against the wind speed derived from balloon measurements, this wind speed is strongly correlated with the wind speed measured at the height of the tropopause. Right: Examples of Cn2 profiles measured in different sessions.

The above results apparently show that turbulence in low layers is more critical for the quality of the communications, nevertheless the combined effect on the channel of turbulence in layers at different heights is definitely complex. It seems therefore that the classical log-normal assumption for modelling error rate performance in weak turbulence is not suited to account for the observed behaviour, more sophisticated channel models should be implemented in order to explain the behaviour in the variety of turbulence conditions observed. In this respect, our purpose in the future is to perform a detailed study trying to find the correlations of measured turbulence moments and BER.

4. CONCLUSIONS

We have conducted more than 50 optical links between ARTEMIS and the OGS (38000 km distance) in different turbulence and weather conditions.

The results obtained in the downlink have proven that stable and reliable laser communication links are feasible through the atmosphere. The short term average bit error rate measured in the downlink is 9.8 10^{-7} (accumulated over 57 links and more than 20 link hours), however perfect links (error free) ranging from 1 minute to 35 minutes has been observed.

In the uplink the satellite receiver could hardly lock on to the signal from the ground station. When locked, the bit error rate never dropped below 10^{-6} with average value around 10^{-3} due to the much higher scintillations. An upgrade of the modulator of the OGS is required in order to analyse properly the uplink communications channel. Furthermore, experiments will be scheduled in order to analyse the statistics of the distribution of error burst in both downlink and uplink.

The effect of atmospheric turbulence on the performance of the communications channel has been analyzed through the comparison of BER with scintillation index, probability and duration of fade/surge at a level of 0.5 dB, residual errors of the spot centroid, isoplanatic angle, and wind speed. Instead of a neat correlation of BER with the several turbulence related parameters, a complex behavior is observed. We are at present working a model in order to explain the results.

5. ACKNOWLEDGEMENTS

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