HF-XL AIRBORNE TRIALS OVER THE ATLANTIC

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SUMMARY

In this paper, we present the results of airborne trials conducted with the French MOD to evaluate the new HF-XL high data rate waveform [1][2][3] in airborne conditions. To monitor and test the waveform, two different tools have been used: a THALES user application currently in operation in different forces, called TMS, and a lab specifically developed tool that generates automatic data traffic to emulate multiple applications or users transmitting over HF, called OMP. This tool will show the statistical behavior of an HF-XL transmission at packet level, hence permitting a more comprehensive analysis of the waveform performance. The trials are conducted on the ATLANTIQUE 2 maritime patrol aircraft flying over the Atlantic. This is simulating a typical operation within a mixed air and naval mission, where the aircraft needs to communicate with ships and ground, represented by two stations located in Lorient and Toulon. The presented trials results shows HF-XL operation during different HF propagations conditions, and at different altitudes, leading to both sea wave ionospheric propagations. We have observed that the HF-XL transmission operates in two modes, depending on the available MODEM data rate versus the total application needs. The first state is a non-saturated data rate, where throughput is higher than the applications needs, where the latency is minimum, and a dynamic data exchange is optimum. The second state is the saturated state, where the latency depends on the propagations conditions and ensures a highly robust, but slow data link.

1 INTRODUCTION

Since mid 2020, we have developed an airborne version of the high data-rate SALAMANDRE HF demonstrator designed to operate via one of the long-wire antennas found on the ATLANTIQUE 2, maritime patrol aircraft (see Figure 1). In April 2022, the French MoD

(DGA: Direction Générale de l'Armement) conducted two tests flights with this set-up, with the objective to validate the airborne capabilities of the new HF XL System.

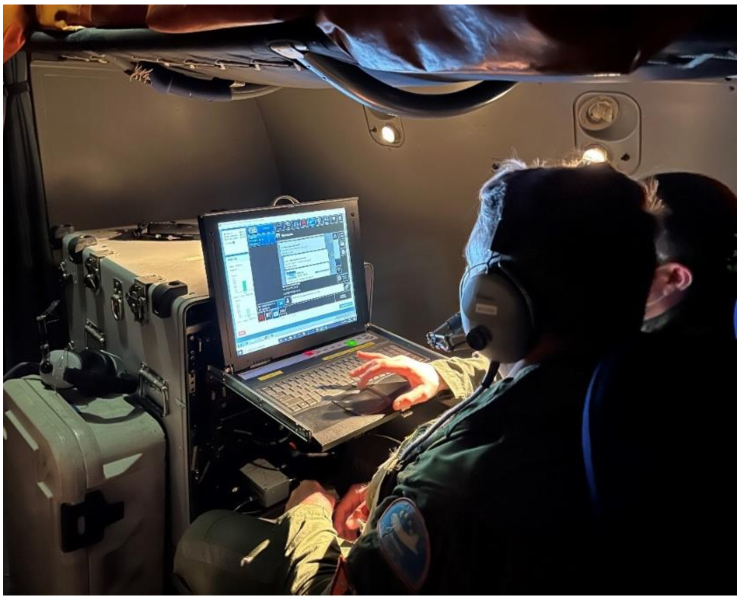

Figure 1: SALAMANDRE demonstrator installation on the ATLANTIQUE 2 aircraft.

The SALAMANDRE demonstrator implements the multi-narrow band, high data rate, HF-XL system that helped the DGA and THALES to develop and validate the new set of HF standards AComP-4203, AComP-4539 Ed A V3 annex H [4], and the STANAG 5070 proposition. Various field trials, in terrestrial and naval conditions, both with or without mobility have been conducted over the years, but these airborne trials are the first ones carried out to validate the HF-XL waveform in an aero-naval environment simulating modern warfare needs in communication between airborne and seaborne platforms

The airborne trials took place during two consecutive days in April 2022, the first early in the morning to assess the night transmission conditions, with mostly a station sea wave with a ground station in Lorient, followed on by long distance ionospheric link on the second day with a more distant station located in Toulon.

1.1 Ground station for day one tests description.

For the day one tests, as illustrated by Figure 2, the ground station was very close to the seashore in Lorient and close to the Lann-Bihoué naval airbase, home base of the ATLANTIQUE 2 aircraft fleet. This station was using a whip antenna to represent a typical ship HF installation in sea-wave propagation conditions and a half loop mobile antenna for NVIS propagation conditions. The take-off was about 2:50 UTC, landing 8:40 UTC. Transmit power for the Lorient station was 400 W_{PEP}.

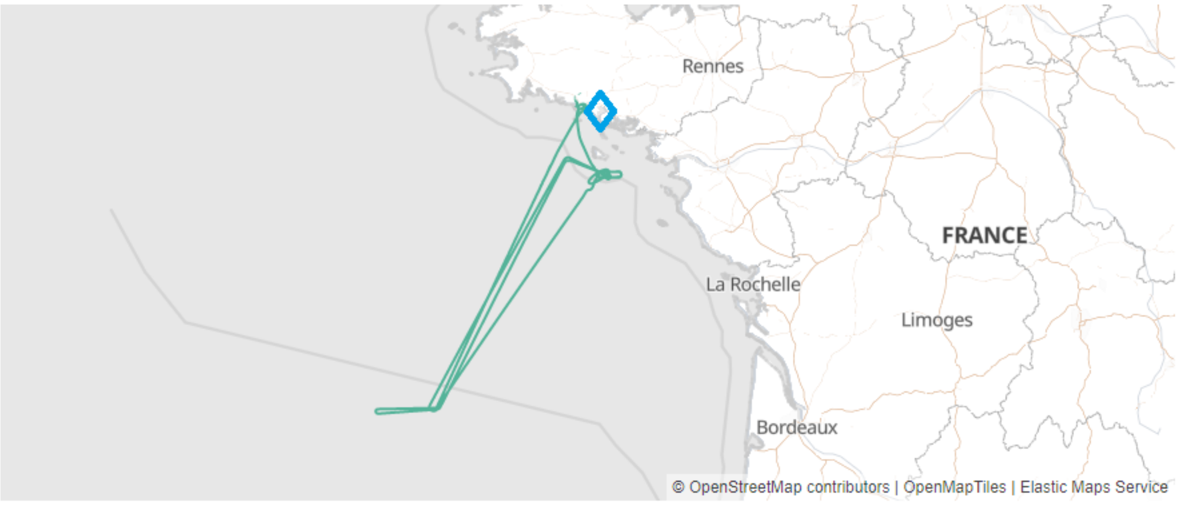

Figure 2: day one trajectory, with the Lorient ground station location in blue.

1.2 Ground station for day two tests description.

As illustrated by Figure 3, Toulon was the ground site for the second day tests. This site represents a typical HF distant ground infrastructure station for ionospheric sky-wave propagation. The antenna set-up in Toulon is a wideband "Volubilis" HF antenna. Take-off was about 9:20 UTC, landing 13:00 UTC. The transmit power for the Toulon station was 1 kW_{PEP}.

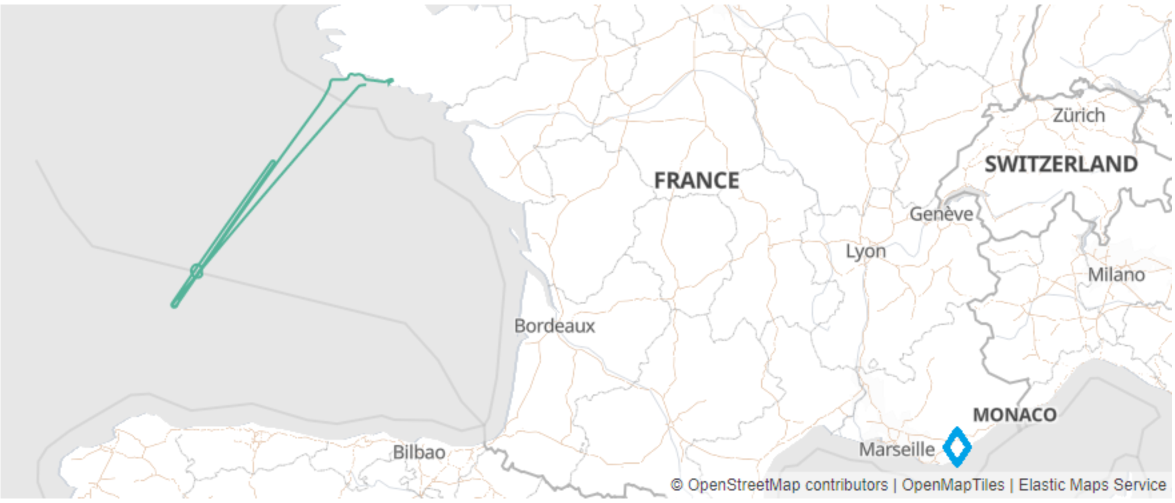

Figure 3 : day two trajectory, with the Toulon ground station location in blue.

1.3 Airborne station description and test setup.

The airborne station transmit power was 150 W_{PEP}. It is connected to a long-wire antenna already installed in the ATLANTIQUE2 aircraft.

The three stations: in the aircraft and in the ground locations have the same applications and identical mission configuration (frequency set in particular). During the flights, we used two data transmissions applications to evaluate the link performance: first, the traditional terrestrial THALES user application called TMS, which is an Email, Chat and data transmission system also capable to plot and share the mobiles GPS positions during the whole flight. This was the main tool used to communicate between the airborne and ground crews.

We also used a THALES custom designed tool written in python [5] whose allows an in-depth comprehension of UDP/IP or TCP/IP packets exchange. This OMP tool (for Outil de Mesure de Protocole in French) regularly sends UDP or TCP IP packets with known size and time. The size and sending time follows know statistics, simulating "real" data traffic, used to analyse the link characteristics available to the applications

The SALAMANDRE demonstrator records all the events from the radio, the MODEM operation, and the individual data packets transmissions metadata. These data, together with the navigation log-file, feed an HAWK data analysis suite, a THALES tool, based on Elastic-Stack, which is used to produce the different data analysis graphs presented in this document. The inherent statistical approach of the analysis permitted to easily average the modem data rate and data rate transmission, which nicely avoids data clutter.

2 TESTS RESULTS.

2.1 Day one, short to medium distance propagation (0 to 380 km)

The first day was dedicated to observation of "sea-wave" or direct wave propagation modes and the analysis of the transition to ionospheric sky-wave. The conditions were late night propagation, before dusk. The ALE (Automatic Link Establishment) selected the lowest frequency for the transmission: 2MHz band which is good for both sea-wave and ionospheric sky wave at short distances. The sea-wave propagation is a typical over the horizon mode between shipborne stations, leading to channel characteristics close to AWGN. Among the key questions was the effectiveness of this sea wave propagation mode and possible impact of aircraft altitude. As such, we needed first to establish the theoretical distance for line of sight propagation with our aircraft.

2.1.1 Conditions for Line of sight propagation.

Using the classical trigonometric formula giving the distance to the horizon from a height of h (see Figure 4) : we find distance d defined as $d = \sqrt{(h + Rt)^2 - Rt^2} = \sqrt{h^2 + 2Rth}$, where Rt is the earth radius, h is the height. For both a ground station and an aircraft remaining in the low layers of the atmosphere, the assumption of h<<Rt is valid and this: $d \sim \sqrt{2Rth}$. This allows to define the maximum line of sight geometric distance between ground station and aircraft, using the two points different altitudes, h_1 and h_2 :

$$d_{tot} = \sqrt{2Rth_1} + \sqrt{2Rth_2}$$

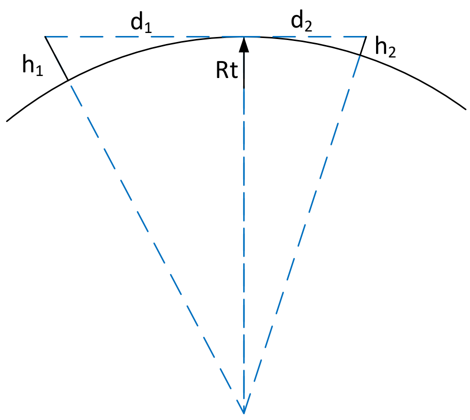

Figure 4: Line of sight geometry calculations

The Table 1 gives the numerical limits for our first day flight. We see that we can count on the surface wave propagation from 0 to circa 280 km for low and high altitude, but probably not much further.

Table 1 : Maximum line of sight distance in function of the altitude of each stations.

h1 [m]	h2 [m]	d [m]
100	6	44464.506
1000	6	121692.256
6000	6	285402.956

2.1.2 Phase A: Over the horizon propagation: further than 300km

Let us first consider a first section of this first flight, called phase A, which did occur at night, when the aircraft was further than 300 km from the ground station. It had been decided to test the influence of altitude in the transmission and as such the aircraft realized a transition from 4000 m to 100 m of altitude (see Figure 5) at distances of 310 to 380 km. The rapid useful data rate link evolution (measured as the protocol data rate) shown in Figure 6 inbound airborne station (while Figure 8 shows results inbound ground station) confirms that the link uses an ionospheric propagation mode. However, no specific impact of the altitude is noted for this low frequency (2 MHz) at night. When the link is difficult, the DRC (MODEM automatic Data Rate Control) will configure the modem data-rate to the most adapted one, in practice often the lower possible value of 1600 b/s (see Figure 8). It is logically observed that the link is not symmetrical in performance: this is in particular due to the amplifier and antenna different performances in both settings.

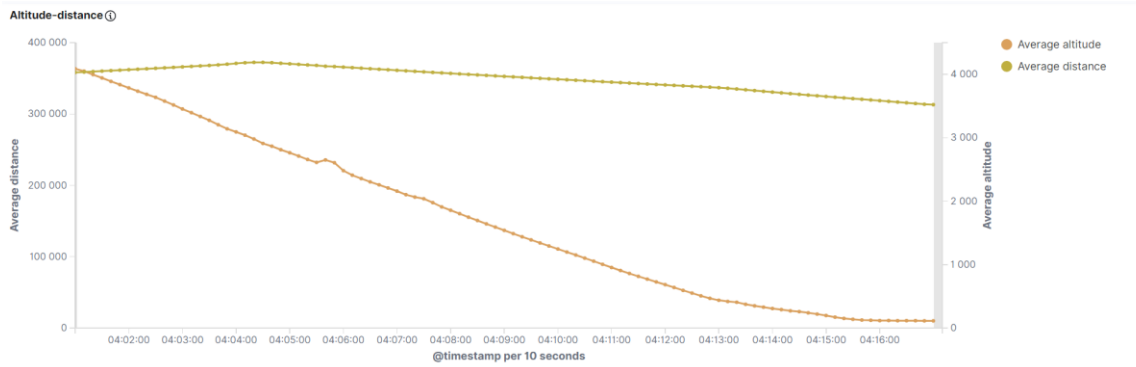

Figure 5: Measures of distance [m] and altitude [m] for the aircraft during first flight phase A analysed.

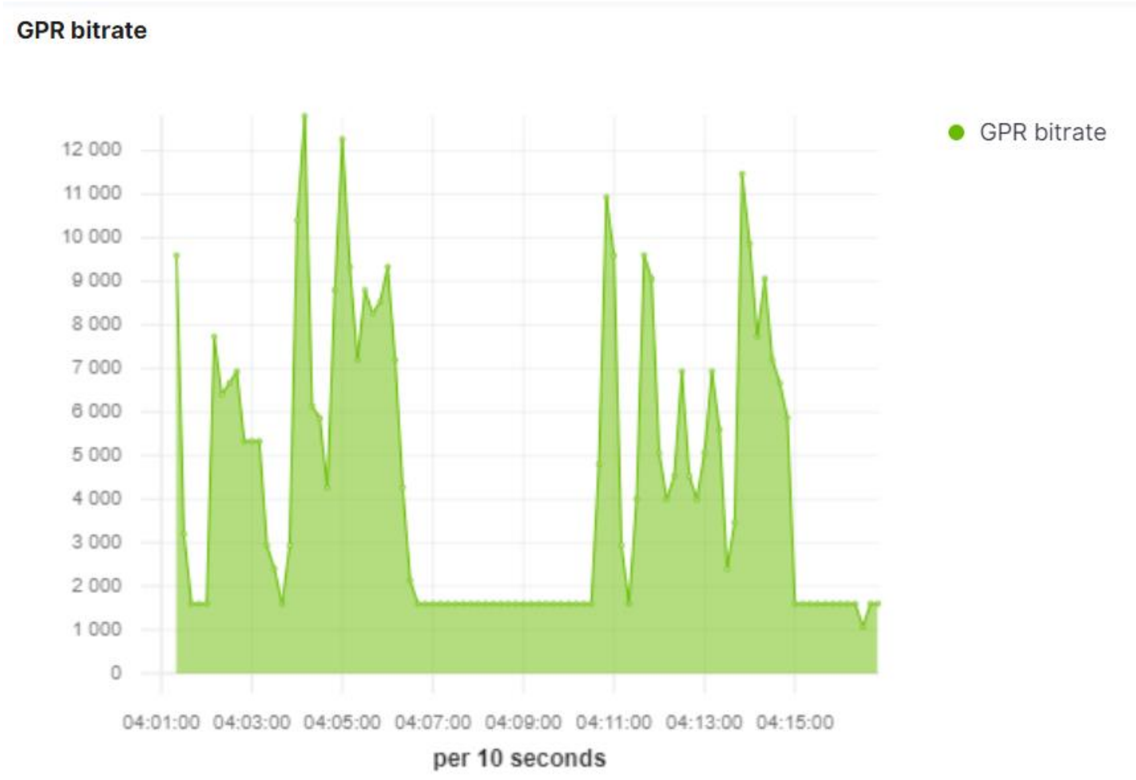

Figure 6: MODEM data-rate [bits/s] vs time at 2 MHz, showing an ionospheric propagation mode inbound airborne station (note: the value shown is an average over 10 s) during phase A.

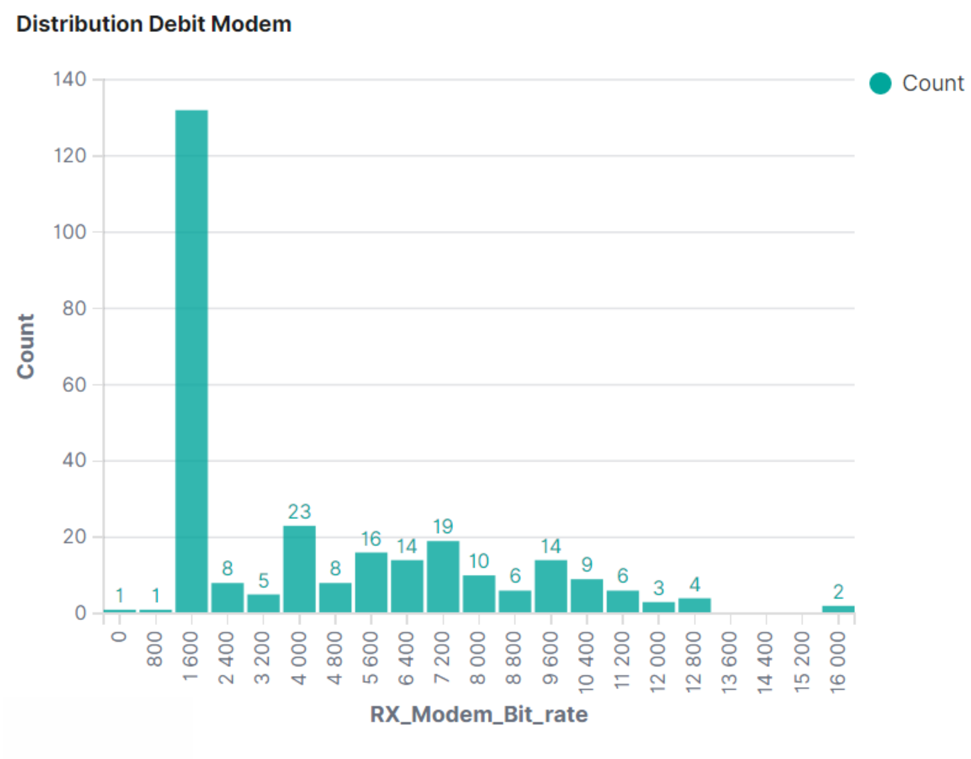

Figure 7: MODEM data-rate statistical distribution during phase A (ionospheric transmission). The fixed 1600 b/s bar is due to the long phase where the airborne antenna shows a lower gain.

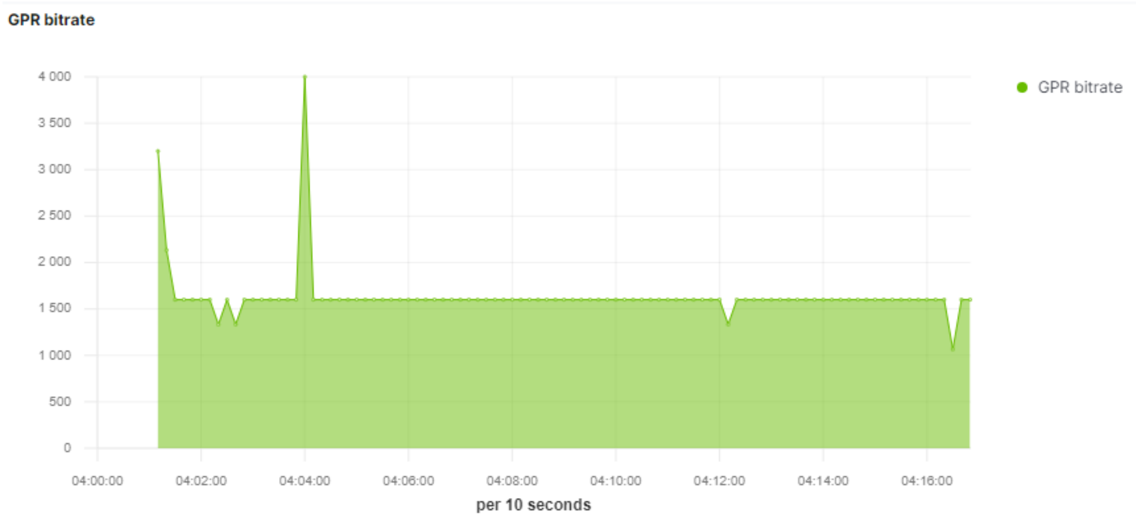

Figure 8: MODEM data-rate in bits/s vs time at 2 MHz, averaged over 10 s, inbound the ground station during phase A.

2.*1.3 Phase B:* Flight back from 300 km to 55 km

Let us now consider a second part of the flight, called phase B, which did occur on the way back to Lorient, when the aircraft was between 300 and 55 kilometers from the ground station (as shown by Figure 9). This flight was done at low altitude (on average 100 m) and allowed to observe the transition from ionospheric sky-wave to a steady sea-wave propagation mode with the typical staircases data rate increase.

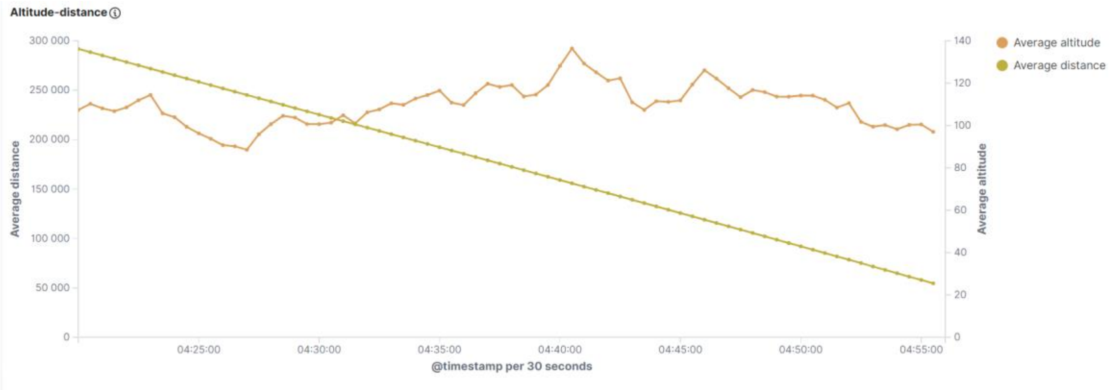

Figure 9: Distance (green) and altitude (brown) during phase B (way back to Lorient).

Figure 10 presents the useful data rate link evolution for inbound airborne station. The observed performance (lower data rate and important variation) show that the link uses ionospheric propagation from 300 km down to 200 km. It must be noted that two manual actions independent of the trials led to two short interruptions of the link, hence the two short periods of data transmission absence in the figure that are not due to propagation conditions.

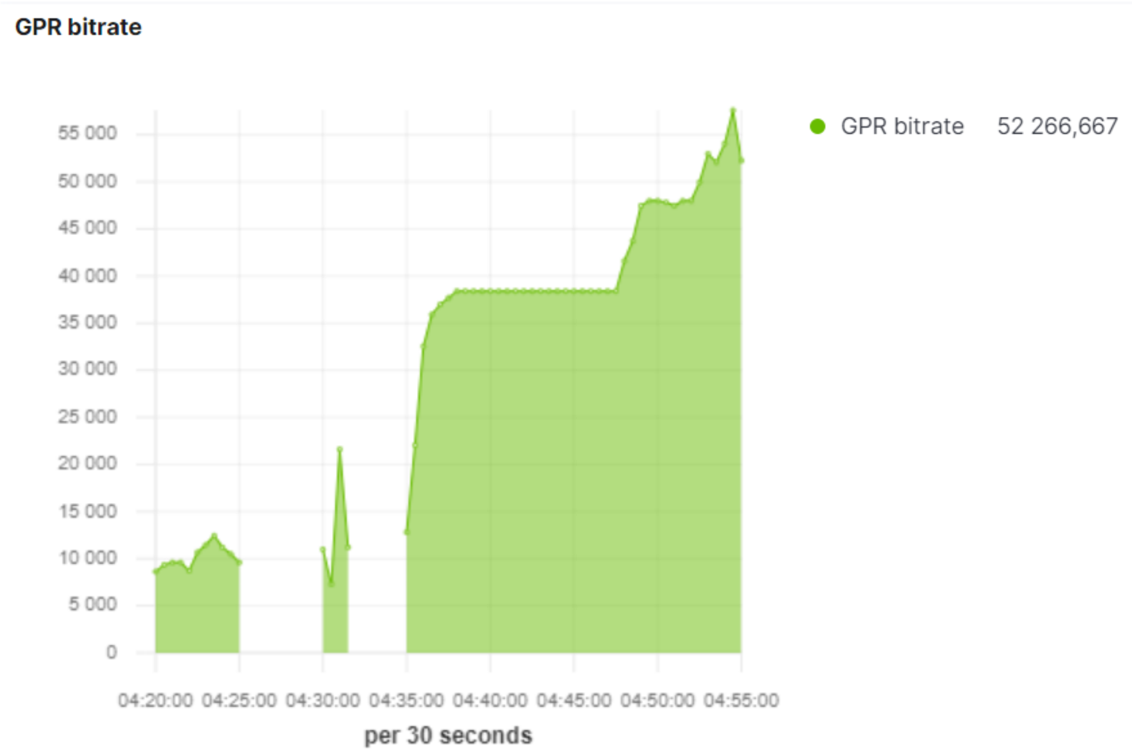

Figure 10: MODEM data-rate averaged over 30 s during phase B, with sea-wave propagation conditions after 4:35 UTC, corresponding to steady sea-wave conditions.

At distances of less than 200 km (after 4:35 UTC), the link shows the stable characteristics of a sea-wave propagation mode with constant MODEM data-rate increasing regularly due to the steadily increasing SNR accordingly to the shorter distances (see Figure 10). We can see the modem data-rate changing from 9600 b/s to 40 kb/s, steadily increasing in the staircase way typical of sea-wave propagation. Accordingly, Figure 11 shows the overall modem data rates during phase B.

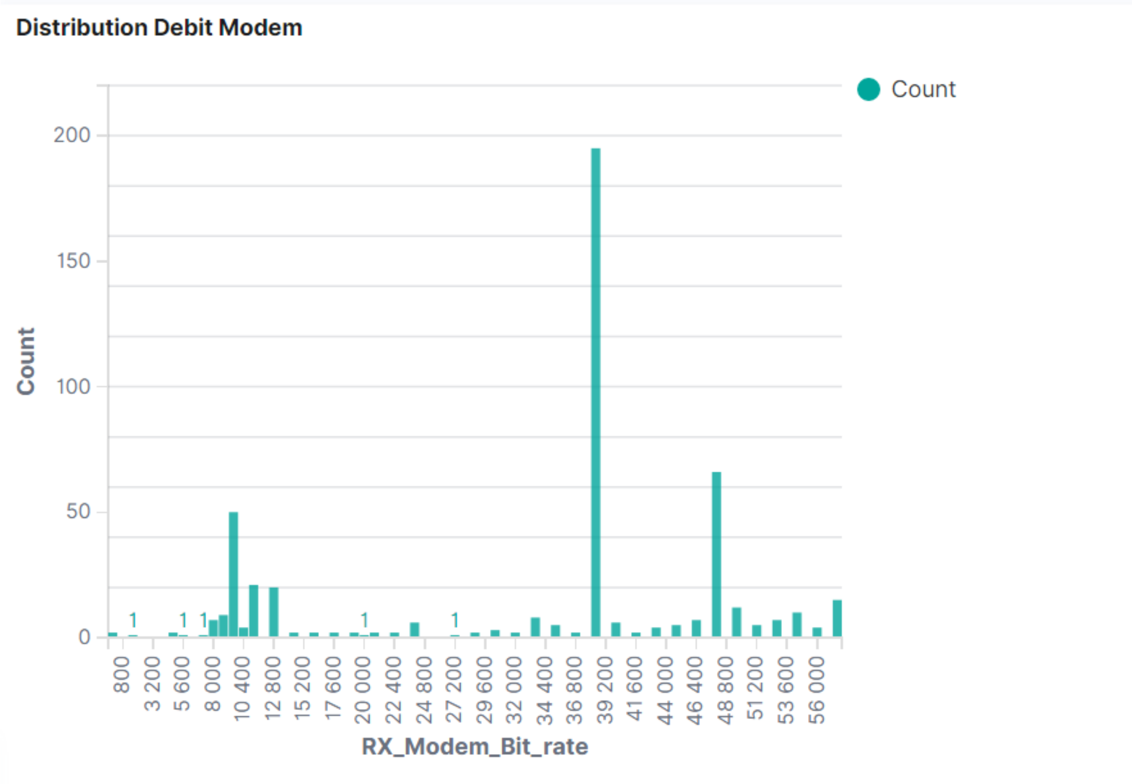

Figure 11: Statistical distribution of the MODEM data-rate in (bits/s) during phase B.

2.2 Day two, long distance ionospheric propagation (930 to 1070 km).

The second day trials, dedicated to long distance link, took place in the morning, daytime. As shown in the results below, the ALE protocol (Automatic Link Establishment) did select XL band center frequencies between 7.5 and 12 MHz, which are typical for such long distance ionospheric sky-wave links. The purpose of this trial was to analyse further the protocol and modem behaviours, and for this the OMP tool was used.

This phase C is illustrated in Figure 12, which shows the OMP IP application data-rate compared with the MODEM data-rate, and in Figure 13 which presents the delay, related to the evolution of the ARQ input queue.

Let us focus on the timestamp 11:36, when the link is lost during about one minute due to a 360° turn realized by the aircraft. The root cause for this event is the uneven radiation pattern of the long-wire antenna. The DRC (Data Rate Control) adaptation speed is slow in comparison to the time variation of the antenna gain, and the relatively low occurrence of such an event does not justify changing the algorithm to adapt to such an issue, especially since the packets are not lost. In fact, during this perturbation, the link delay increases (see Figure 13) indicating that the packets are accumulating in the ARQ input queue, waiting for errorless transmission. When the link resumes around 11:37, we can see at the same time an increase in the IP data-rate (flushing of the queue) and a fast decrease in the delay indicating that the ARQ is emptying its input queue at fast pace.

This illustrates clearly the link management effectiveness that combines the DRC and the ARQ to keep the connectivity by adjusting the transmission parameters. This also emphasizes the actual effect on the IP data link, its robustness, and that potential natural link disruption will not affect applications if their time out are sufficient.

It must be noted that the data rate drop from 11:43 to 11:46 is due to a change in the OMP application configuration, and not due to propagation conditions.

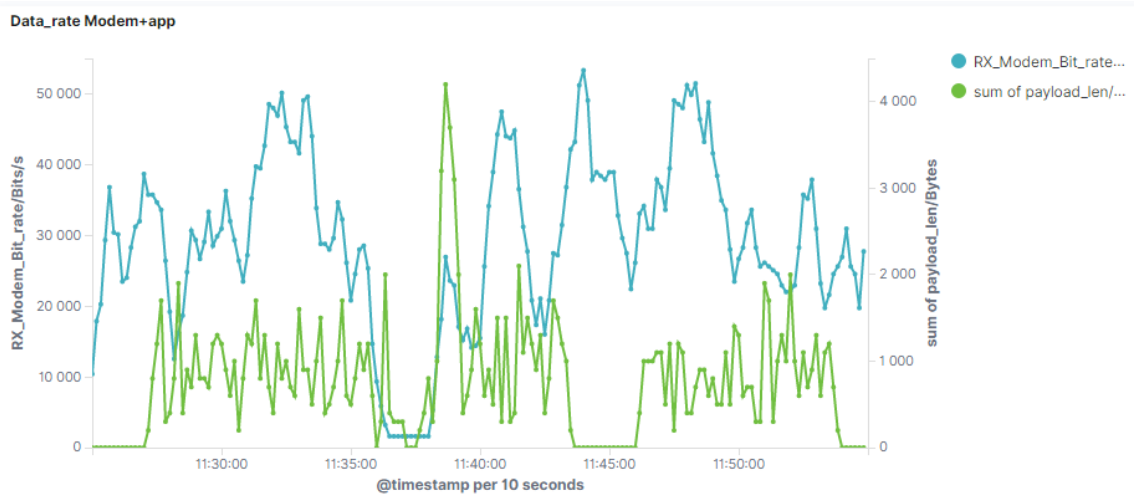

Figure 12: MODEM data-rate in bits/s averaged over 10 s (blue), and IP received throughput in bytes per 10 s (green) during phase C.

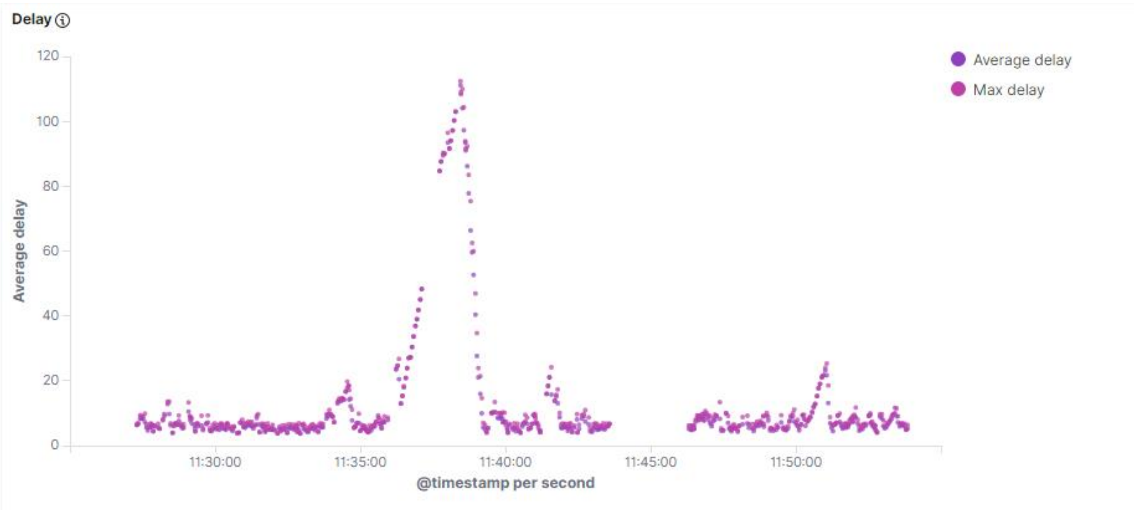

Figure 13: IP packet data delay during phase C.

2.3 Statistical properties proposition for IP packet transport over HF data link.

From a user application standpoint, it is usually of prime concern to have a good description or model for the link capabilities at an IP packet transport level. With widely used line of sight radio link such as LTE, UMTS, WIFI or even VHF/UHF military communication systems, many tools and models are available. However, for the data transmissions that use the HF media, there is no description, neither a theoretical nor an empirical model that takes into account the unpredictability usually encountered in HF ionospheric transmissions.

While obviously only a few days trials is not sufficient to establish such models, we took the opportunity of these tests and the availability of live measurements to begin to analyse this problematic.

As a first approximation, the TDD (Time Division Duplex) channel access scheme used by HF XL waveform delivers the IP data packets in a discrete time manner: with the parameters used in these trials, it means that every ~3 s all the received packets are transferred to the receiving applications. The DRC selects the data rate for each slots, defining consequently the maximum amount of data transmitted on each received slot, i.e. every ~3 s.

We can further identify three characteristic conditions that describes the total amount of data transmitted for each slot: the steady sea-wave propagation condition, generally obtained with a high SNR; the sky wave ionospheric conditions with high SNR and the sky wave ionospheric difficult conditions with low SNR. Each of these conditions shows some statistical characteristic properties that are of prime interest to quantify and model an HF link seen from the IP packet transport standpoint.

The statistics presented in the following sections are the received modem data-rate of each slot plotted as a histogram, the count being the number of slots.

2.4.1 Case 1: Steady sea-wave or ground-wave characteristics.

Even more that with classical narrow band 3 kHz transmission, sea-waves or ground-waves show with HF XL waveform stable propagation characteristics with relatively good SNR, which allows the DRC to select the best waveform maximizing the data throughput between the transmitter and the receiver (see Figure 14). The statistical histogram distribution for the MODEM data-rate shows a typical narrow bar characteristic, with a very small variance (close to AWGN transmissions).

With an airborne station whose relative speed leads to a faster variation of the distance than with a ship or terrestrial vehicle, changing the received signal power equally faster, we see a regular change in the modulation and MODEM data rate. This change is not continuous with the time but follows a staircase shape as illustrated by Figure 11.

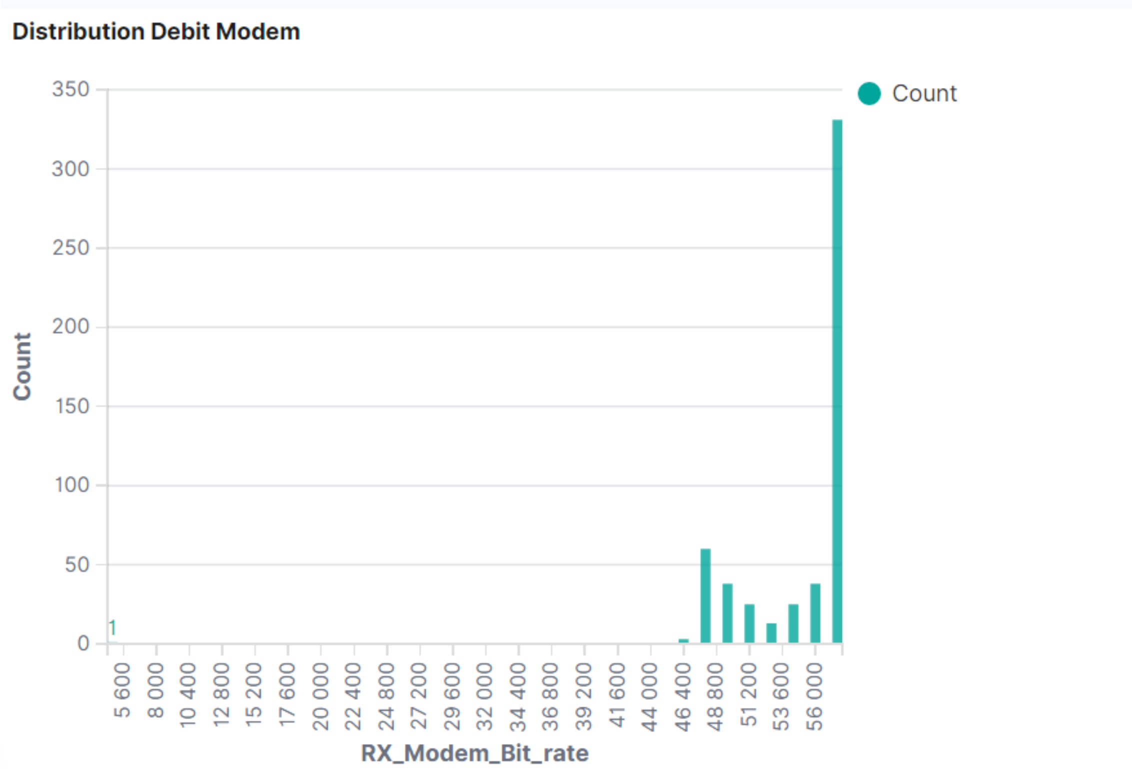

Figure 14: sample statistical MODEM data-rate 5:40 to 6:10 in a steady sea-wave conditions, day 1.

2.4.2 Case 2: High SNR ionospheric HF link

Figure 15Figure 16 and Figure 16 show typical MODEM data rate histograms in long distance ionospheric sky-wave condition. The first one (Figure 15) presents only a 10 minutes timespan while the second (Figure 16) is averaged on the second day entire mission. In both cases, we see the classical bell shaped curve typical to stochastic processes with a large variance. This variance in the Figure 15, fFigure 16 and (and that will also be loosely seen in Figure 17) is a key signature of actual ionospheric transmissions, not shown in sea-wave transmissions or with an ionospheric RF link simulator implementing the Watterson model [5], [6].

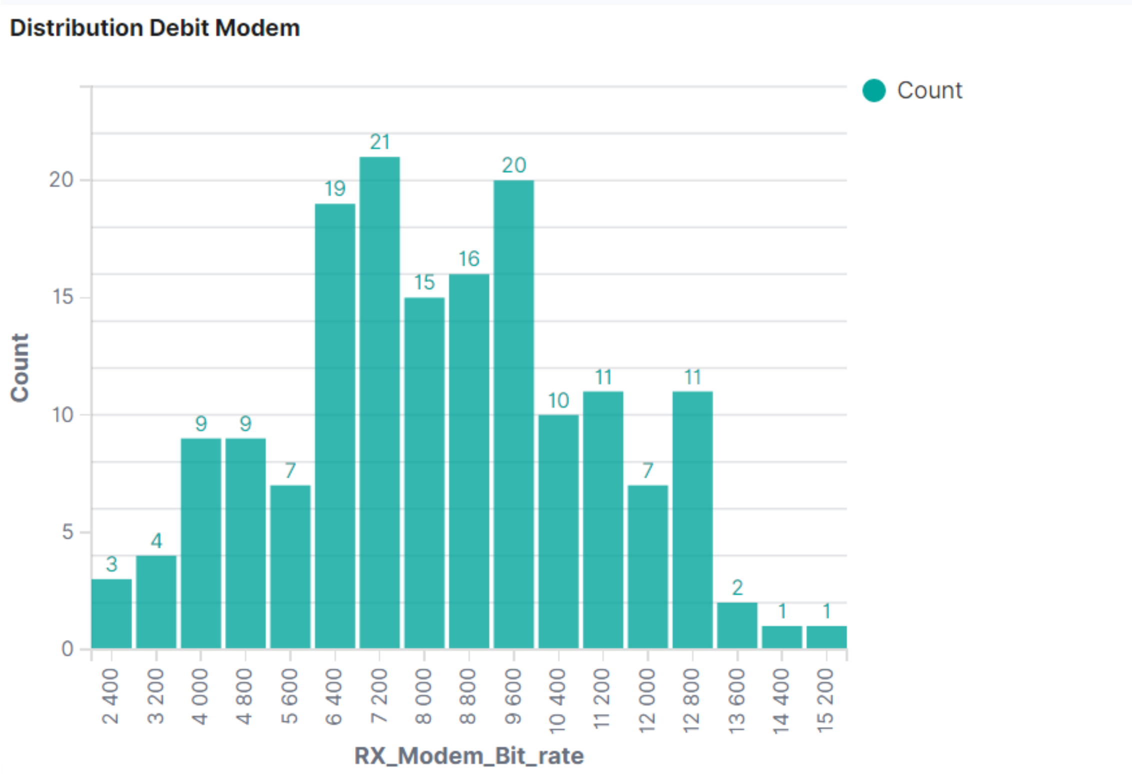

Figure 15: sample statistical MODEM data-rate medium speed 9:22 to 9:32, day 2

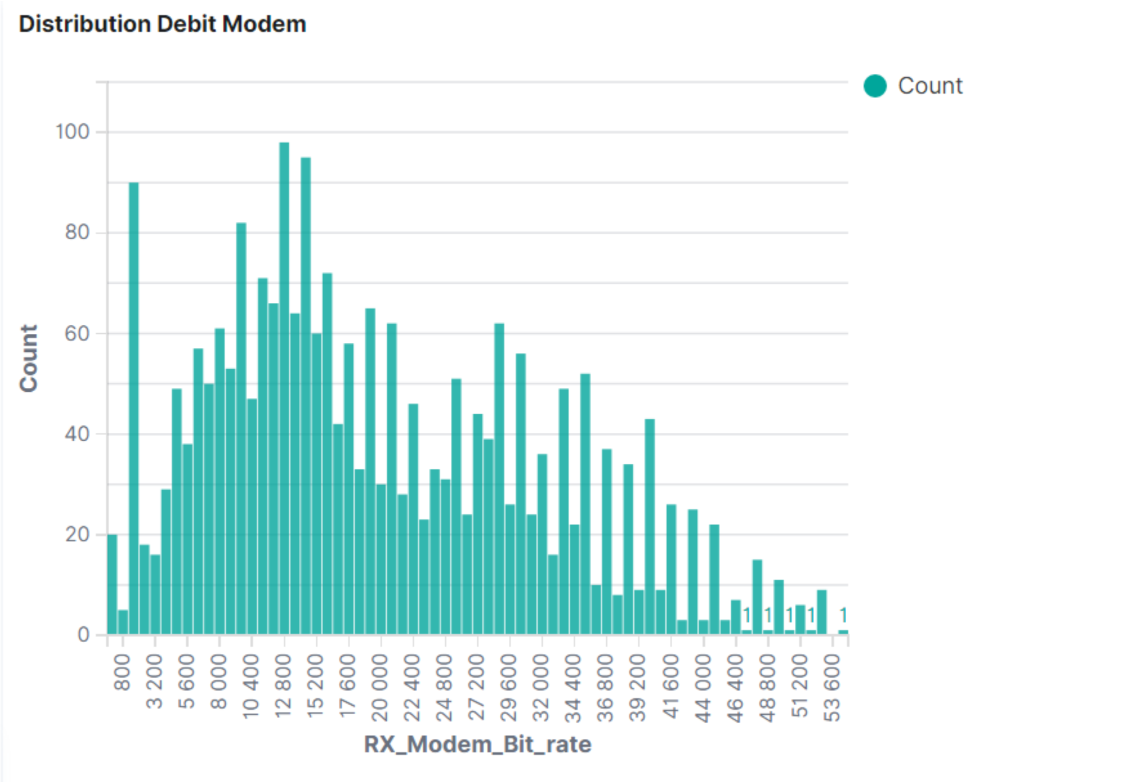

Figure 16: sample statistical MODEM data-rate for the whole mission, day 2, link as received by the airborne station.

2.4.3 Case 3: Low SNR ionospheric HF link

The link between the aircraft and Toulon shows a lower link budget with a mean SNR lower than the ground to air link due to the lower transmitting power and lower antenna gain on the aircraft. The Figure 17 shows the MODEM data rate with lower mean value. The obtained distribution is also impacted by a big bar at 1600 bits/s, which is due to the DRC being unable to select a lower data rate. This feature ensures that the link remains connected in difficult conditions by selecting the lowest possible data rate. This leads to higher transmissions errors corrected with increased packet repetitions.

The measured MODEM data rate histogram shown in these ionospheric HF conditions gives us some insight to simulate an actual ionospheric link on the IP transport level (Figure 15, Figure 16 and Figure 17). Based on this very preliminary analysis, a Gamma stochastic distribution with the good parameters could be a good candidate to represent the MODEM data-rate for each slot.

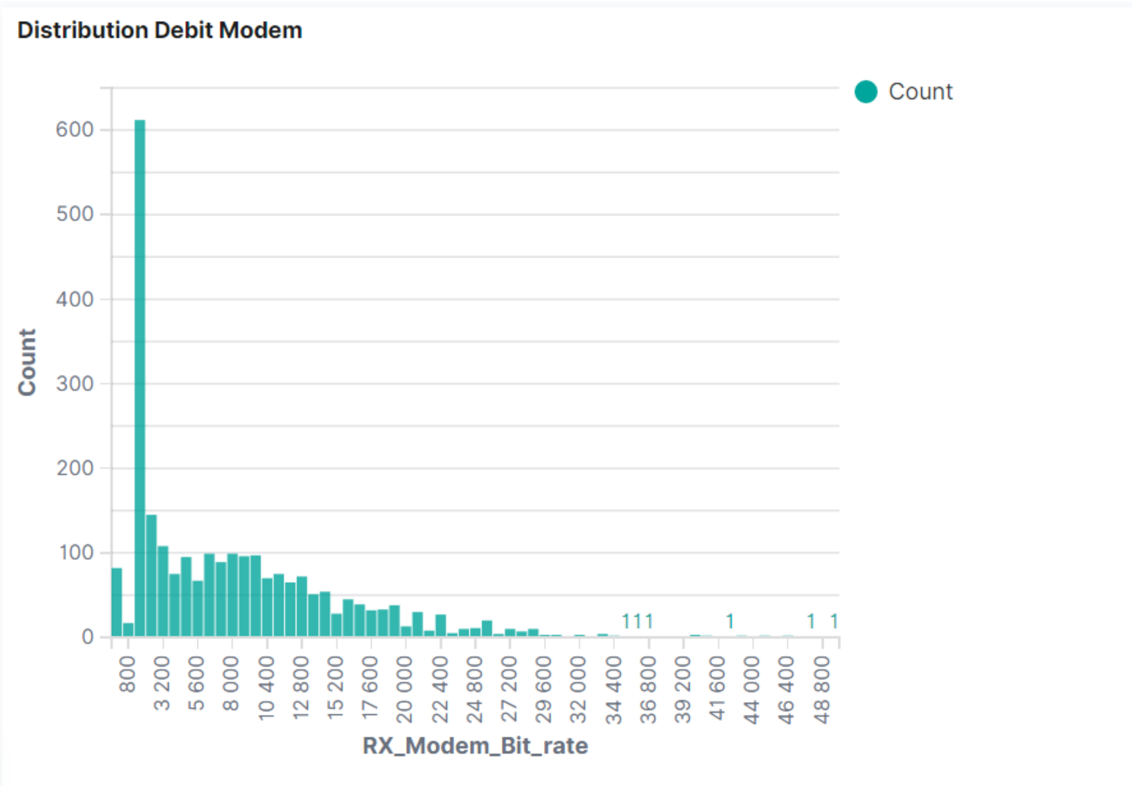

Figure 17: sample statistical MODEM data-rate for the whole mission, during the day 2 link as received by the Toulon Ground station.

3 CONCLUSIONS

During April 2022, the SALAMANDRE team (with DGA and THALES members) was able to equip and operate an airborne HF-XL station on an ATLANTIQUE 2 Marine patrol aircraft.

Two different hours long flights in the Atlantic over the Biscay Bay allowed the team to test and validate many propagation conditions typical to the expected missions.

The first flight showed that sea-wave propagation conditions extends from 0 to about 200 km, and is not dependent of the altitude. Over this distance, the transmission switches from sea-wave to ionospheric sky-wave propagation at night and early morning. The SALAMANDRE system adequately selected a 2 MHz frequency.

The second flight was a morning flight, dedicated to long distance, around 1000 km, to test and validate ionospheric transmission between an airborne station and a ground station. This experiment showed that the link is available and easy to establish thanks to the SALAMANDRE system. We showed that it is robust to adverse propagation conditions that can happen during the aircraft maneuvers. During these flights, we had the opportunity to record many data that allows us to realize a first statistical analysis properties for the transmissions that will be of great interest for link simulation at the IP transport layer.

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