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AMORES Robotics Telemetry Radio

In-Field Performance Evaluation

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This publication is up-to-date with TeRad board version 1.1 and software version 1.00.

Please check our website for product upgrades.

Contents

1 Introduction

This document reports an in-field performance evaluation test designed to assess the real world performance and capabilities of the AMORES Robotics Telemetry Radio (TeRad).

TeRad is a lightweight digital radio module operating in the 868 MHz ISM band, specifically intended for use onboard UAVs (drones). It provides a bi-directional serial communications channel between the UAV and the ground station, geared towards in-flight telemetry and control purposes.

The performance evaluation test reported below has been designed to assess the real-world capabilities of AMORES TeRad, and was thus performed in an environment that is very close to intended real usage conditions. We hope that the availability of such information will be of great significance to those evaluating TeRad as a possible option.

This publication is a companion to the **AMORES Robotics Telemetry Radio Handbook**. Please consult the *Handbook* for detailed product information.

2 Evaluation experiment

The performance evaluation was done with a radio link between a stationary ground endpoint and a counterpart onboard a fixed-wing UAV (drone). The UAV took off in the vicinity of the ground station, and after reaching an altitude of 100 meters above ground, proceeded to fly away along a straight line towards a remote landing site distanced 15 km from the ground station.

The telemetry radios were set up to operate in Diagnostic mode, generating test traffic between themselves and measuring link quality, error correction usage, packet loss, RSSI and link distance among other operational parameters (see the **AMORES Robotics Telemetry Radio Handbook**, section 6 for a detailed description of Diagnostic mode – it is available for your own usage as well). The diagnostic output from the ground station’s radio endpoint was logged throughout the journey. This log forms the basis of all quantitative information presented in the below report.

The flight route took place in Pest county, Hungary, along and in the close vicinity of the (mostly straight) country road between villages Kunpeszér and Bugyi. The UAV was flown by an onboard autopilot (ArduPilotMega) executing a pre-programmed route plan. Takeoff and landing was performed manually via RC.

Points of interest (please see the Appendix in section 5 for a map of the route):

- **G** ground station, takeoff site: north of Kunpeszér village, N47°4’28.05", E19°15’13.23", AMSL 92m
- **L1** landing site: N47°9’39.87", E19°10’23.53", AMSL 93m, distanced 11 km from **G**.
- **L2** landing site: N47°11’40.78", E19°9’25.81", AMSL 92m, distanced 15 km from **G**.

Two antenna arrays were used at the ground station:

- **O** (*omni*) array of two ground plane antennas on a telescopic plastic stand, 10 meters high above ground (ANT1 and ANT2)
- **Y** (*yagi*) array: two coupled yagi antennas (ACY15) on 8 meter high aluminium stand above ground, set in flight direction (ANT1) and an omnidirectional Amores dipole (ANT2)

The in-flight radio was equipped with two Amores dipoles, one with vertical and another with horizontal polarisation.

All TeRad units under test (both in-flight and the ones in the antenna towers) were set up to operate with antenna diversity. Detailed device configuration:

```
AMORES Telemetry Radio v0.99  build Apr 14 2014

Operating mode      Diagnostic: link quality assessment
Radio setup         High: 95/52 kbps
Radio channel       Ch 5: 869.0 MHz
Link address        0xF9
Error correction    ON
RF booster          ON
Pre-boost TX power  +7 dBm
Antenna             Diversity
Datagram framing    None: transparent serial link
UART baudrate       115200
UART parity         None
UART stopbits       1
UART flow control   RTS/CTS
```

This configuration has a payload capacity suitable for commercially available MAVLink-based systems (eg. Ardupilot family).

2.1 Performing the experiment

The measurement consisted of two flights. After the first takeoff near the ground station, the aircraft proceeded to fly in a straight line towards the remote landing sites. At a distance of 11 km, it flew close by **L1**, eventually landing at a distance of 15 km at **L2**. The second flight started taking off there and ended with landing at **L1**. Flight altitude throughout the flight proper was at least 100 meters.

Flight sections:

- **1A**: first flight, from zero distance to about 7 km, omni array
- **1B**: rest of first flight (distance 7 to 15 km), yagi array

- **2A**: first (and longest) part of second flight with yagi array
- **2B**: short interval (30 seconds) switched to omni array
- **2C**: switched back to yagi array, aircraft headed towards **L1**
- **2D**: shortly before landing, switch to omni array (30 seconds)

2.2 Raw measurement data

Complete diagnostic log output recorded at the ground station throughout the measurement: `rawlog.txt`
Logs of individual flight sections:

- **1A**: `log_1A.txt`
- **1B**: `log_1B.txt`
- **2A**: `log_2A.txt`
- **2B**: `log_2B.txt`
- **2C**: `log_2C.txt`
- **2D**: `log_2D.txt`

Please refer to the zipped archive `AMORES_TeRad_PerfEval_logs.zip` containing all the above log files, available as a separate download.

Estimated link distances in the above logs have been manually corrected for short periods following array (and radio) switches. This was necessary due to the high time constant of the exponential averaging done by the distance estimator. Due to this averaging the radio takes a couple seconds to produce a good link distance estimation, if switched on at a long distance. Estimated link distances during the period of settling in have been manually changed to 'good' values based on the results produced at the end of the previous flight section.

Accumulated logs for each of the two antenna arrays:

- Omni array **O** (1A, 2B, 2D): `log_O.txt` (total time: 12:59)
- Yagi array **Y** (1B, 2A, 2C): `log_Y.txt` (total time: 29:48)

3 Analysis

The experiment was highly successful: a good quality link persisted throughout the flight covering the whole distance range from zero to 15 kilometers. Quality degradation (with significant dropouts) was observed only when, due to the impending landing of the aircraft, its altitude started to drop.

3.1 Propagation model

We begin by evaluating a simple propagation model, seeing how it fits the data collected from the TeRad diagnostics.

According to basic propagation theory, the measured RSSI should be a function of the link distance taking into account

- the free space propagation loss (FSPL);
- transmit power and antenna gain;
- terrain effects (reflection).

3.1.1 Free space propagation loss

The free space propagation loss with SI units: $\mathsf{FSPL} = \left(4\pi d \frac{f}{c}\right)^2$

Using customary radio engineering units (dB, km, MHz): $\mathsf{FSPL_{dB}} = 20\log d + 20\log f + 32.45$, wherein substituting $f = 869$ MHz yields $\mathsf{FSPL_{dB}} = 20\log d + 91.23$. The following table covers the distance range we (as TeRad users) might be interested in.

Rule of thumb: a +20 dB increase in link margin is equivalent to a factor of 10 in distance; +6 dB equals a factor of 2.

d [km]	FSPL [dB]
0.1	71.2
0.2	77.3
0.3	80.8
0.5	85.2
1	91.2
2	97.3
3	100.8
5	105.2
10	111.2
20	117.3
30	120.8
50	125.2
100	131.2

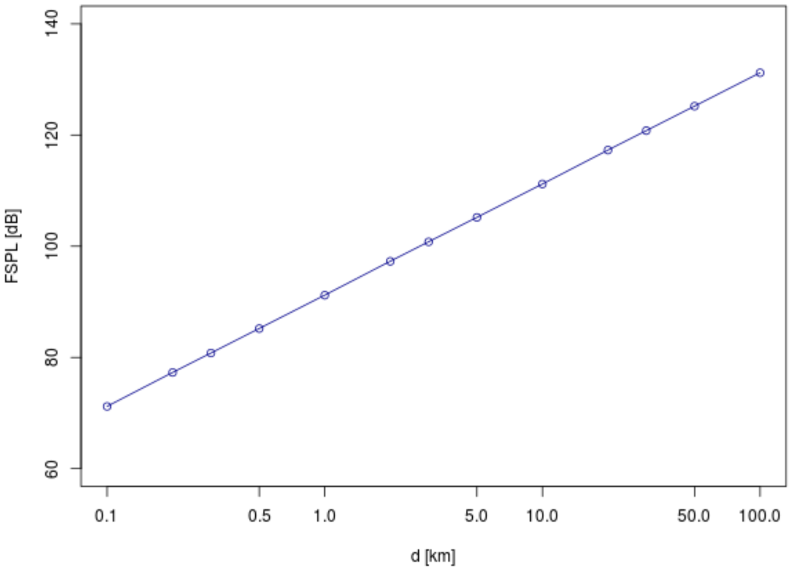

Figure 1: Free space propagation loss ($f = 869$ MHz)

3.1.2 Transmit power and antenna gain

These only act as a constant offset: the greater any of them, the stronger the received signal.

3.1.3 Terrain

A simple over-the-ground propagation model with one direct signal path and one reflected signal suggests a maximal deviation of ±6 dB from the signal level determined by the FSPL and total gain.

3.2 Model evaluation

The two flights cover the whole distance range of our experiment with two different antennas. They are thus ideal for evaluating our simple model.

The following figures plot measured RSSI min/max/avg values against the link distance as estimated by the radio itself. A total gain (antenna gain + transmit power) is then estimated with which the simple model is plot over the scattered data points. Naturally, the estimated gain will be different for each antenna array.

Figure 2 contains three subplots covering all measured data. It is interesting to see how well our simplistic model fits the measured data. The omni antenna has very low gain, estimated at 2 dB. Taking into account the nominal transmit power of +26 dBm, we arrive at a total gain of +28 dB above the theoretical FSPL

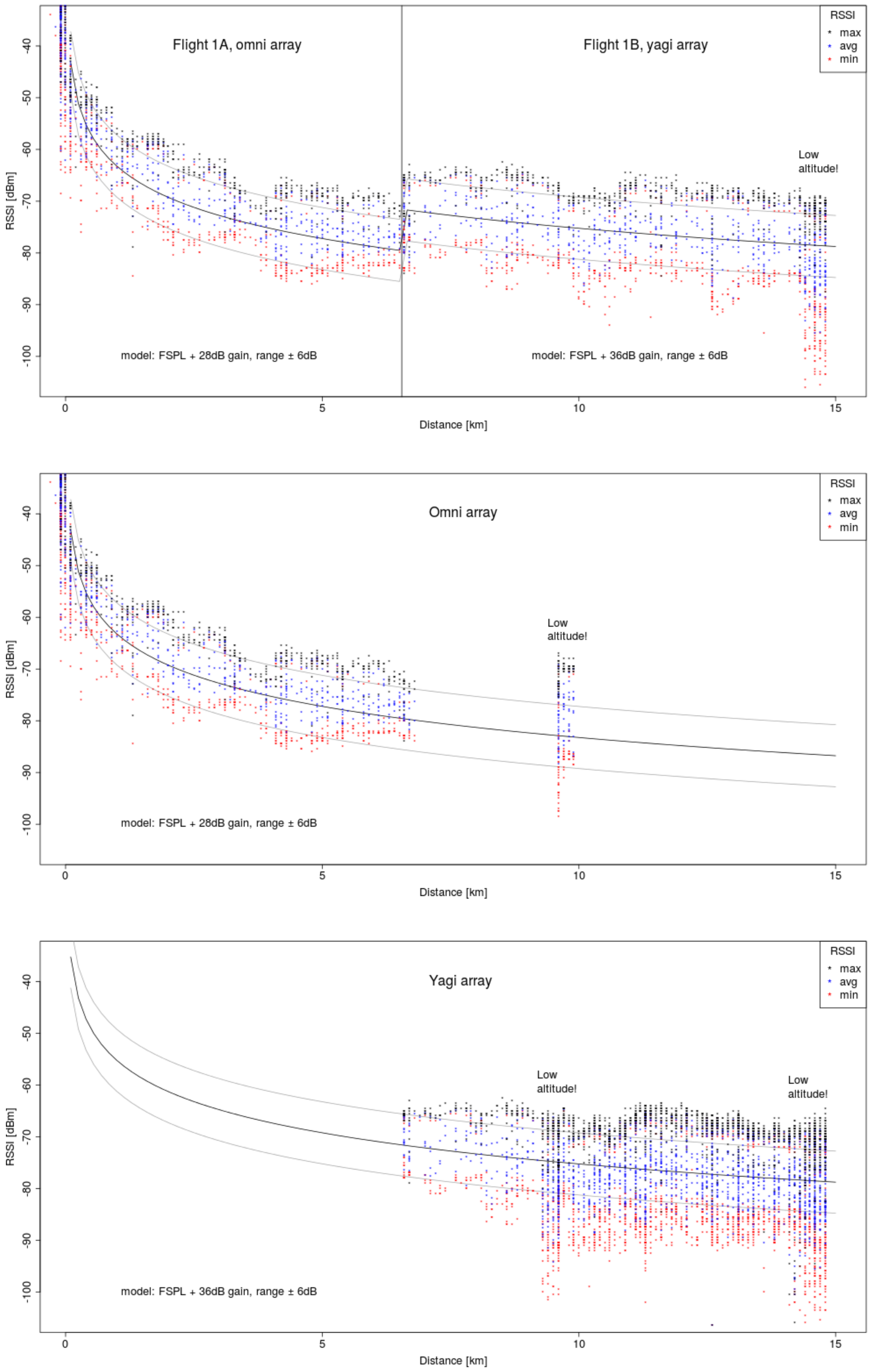

Figure 2: Propagation model evaluation results

(note that RSSI levels are also measured in dBm by the receiver, so 0 dBm is the reference – unit gain – level). This is our estimated total gain for the omni model.

The yagi array does not seem to be that much better than the omni: the model gain only needs to be increased by 8 dB to fit the measurement data, yielding an estimated antenna gain of 10 dB for the yagi array.

The first subplot shows data from the first flight covering the whole range with two arrays: the first seven kilometers with the omni array (two ground plane antennas) and the rest with a yagi array on one antenna connector and a $\lambda/2$ dipole on another (but, as noted later, the diversity algorithm decided in favour of the yagi array throughout the flight).

The second subplot shows all data collected via the omni array (flight sections 1A, 2B, 2D). It is especially interesting that even with these essentially no-gain antennas, a link at a distance of 10 km was still successfully established (this is visible as a separate patch of measurement points towards the right of the figure). These measurement points come from flight sections 2B and 2D.

The third subplot shows all data collected via the yagi array. This array was used at larger distances only (flight sections 1B, 2A, 2C). It shows that the weakest point of our model is the assumption of two-way propagation (one direct path, one reflected path). It clearly shows that the variations in signal strength are greater than the ±6 dB predicted by that model (more reflections – stronger fading).

'Low altitude!' marks are placed on all plots where significant degradation due to landing was observed. It is important to note the key significance of antenna height! Even our handheld CB radios with 4W transmit power at 446 MHz became unusable at a distance of 3-4 kilometers (held 1-2 meters above ground). Compare this with the transmit power of 400 mW of TeRad at 869 MHz: with a tenth of radio power, we were able to maintain a digital data link over a range of 15 kilometers. The difference: 8-10 meter high antenna stands at one end, and an aircraft at an altitude of 100 meters at the other end.

Please note

According to our experiments, properly placed **elevated** antennas are the single most important factor in achieving a robust, long range link with TeRad!

3.3 Achievable range

One of the most interesting questions with any telemetry radio is the overall useful range one can achieve using it. The telemetry/control link is a mission critical component of any unmanned aircraft system, so it is very important to recognize the extent of usable range and carefully take it into account when planning the mission. Range is of course influenced by many factors, especially in the case of a moving, fading-prone link to a vehicle (as opposed to a fixed, stationary point-to-point link). The TeRad diagnostic mode is made available to end users of the product so they can conduct their own quantitative and qualitative link assessments and range experiments based on similar data as that summarized in this report.

According to the above plots, there is a variation of at least 16 dB of signal strength at any distance, with any antenna, throughout the flight. This is mostly due to radio propagation factors (terrain, relative position of antennas with respect to their polarisations, etc). To place this into perspective, let's remember that when calculating free space propagation loss, a 10 dB change in signal power is equivalent to a factor of 2 in distance. For this reason, the link distance achievable with such a dynamically moving radio setup is not very exact – a signal strength variation of 16 dB is equivalent to a factor of 6 in link distance!

As our experiment has proven, a link distance of 10 kilometers is well within range with essentially no antenna gain, but with elevated antennas (8-10 meters above ground) and diversity. Another 10 dB of link margin remained at this point, based upon the sensitivity of the radio input determined via laboratory testing. It seems safe to speculate that given the above circumstances, additional several kilometers would have been available without significant link degradation.

It is also important to note that our results pertain to the configured radio setup of TeRad, namely the ‘High’ speed setting giving 95 kbps payload capacity without ECC and 52 kbps with ECC. In our experiment ECC was enabled. In the absence of radio interference from other devices, lower speed modes should yield greater usable link distance and vice versa.

3.4 Diversity operation

Unfortunately, we did not have the means to record the diagnostic output of the radio onboard the aircraft. However, there are some interesting observations to make based on the ground station radio logs.

The omni array consisted of two identical ground plane antennas. The aircraft radio had also two identical (dipole) antennas with different polarisations (horizontal and vertical). The logs recorded via the omni array indicate that the two ground plane antennas were indeed chosen in roughly equal amounts by the TeRad software throughout different parts of the flight.

The yagi array consisted of two yagi antennas resulting in high gain (according to our model fit to the measurement data, about 10 dB) on the ANT1 connector of TeRad, with another dipole (no gain) on ANT2. It is perhaps not very surprising that while on the yagi array, TeRad exclusively chose the ANT1 signal – the yagi was always giving a much better signal than the dipole.

3.5 Link quality

There are several indicators on the basis of which link quality may be discussed. Here we will look at the number and distribution of fragment retries, number of lost datagrams and error correction usage.

3.5.1 Fragment retries

The following data is derived from the `lp_retry_stats` line printed each minute. Please refer to the *Handbook*, section 6.1.1 for a description. In a nutshell: each datagram is transferred by TeRad in fragments, according to a selective acknowledge-retry scheme. Each datagram may be transferred with no retries (all fragments are received correctly at the first transfer of the datagram) or with a certain (limited) number of retries, during which all outstanding (not yet acknowledged) fragments are transmit again. Figure 3 shows summed fragment retry statistics for both antenna arrays. We attribute the visible difference between them to the fact that the yagi array was used for weaker signals at a greater distance where the bit error rate was higher.

Retries	Omni	Yagi
none	974	724
1	245	627
2	88	275
3	48	193
4	17	72
5	10	50
6	4	40
7	2	20
≥ 8	3	7

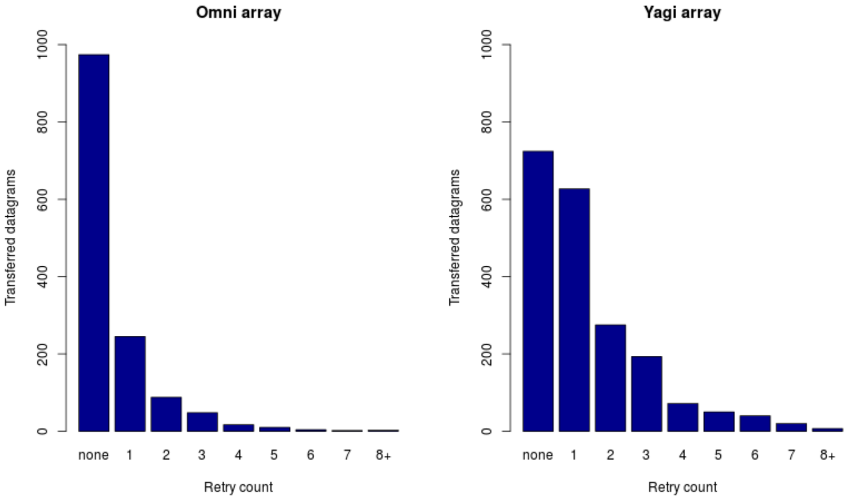

Figure 3: Fragment retry statistics

3.5.2 Lost datagrams

The following table summarizes some statistics calculated from the error counters read from the raw logfiles.

	Omni	Yagi
lost datagrams (RX)	3	30
lost datagrams (TX)	22	86
successfully transferred datagrams (TX)	1391	2008
datagram loss percentage (TX)	1.6%	4.1%

Datagrams lost on the receiving side manifest themselves as logical packet sequence number mismatches. Datagrams lost on the transmitting side are those that could not be successfully transmitted in the allotted 8 retries and were thus dropped. Again, we attribute the greater loss percentage on the yagi array to the fact that it was used with much weaker signals, yielding a higher bit error rate.

Please keep in mind that the test traffic of TeRad's diagnostic mode consists of datagrams with a size of 1023 bytes in order to stress test the software and the link. For real datagrams with a much smaller average size (for example MAVLink packets of 50-80 bytes or even less) the datagram loss percentage should be significantly lower.

3.5.3 Error correction usage

Figure 4 shows histograms of the distribution of ECC corrections per second for each array, as performed by the local receiver and by the remote endpoint. Knowledge of the latter rates are made possible via the so-called 'metadata subchannel' implemented in the TeRad software. This is a dedicated service channel for continuously synchronizing certain operational data between the two endpoints of a TeRad link. It uses a small fraction of each fragment packet (2 bytes beside every 64 bytes of payload). It is via this subchannel that the remote endpoint's certain operational indicators are made available in the output of the TeRad diagnostic mode.

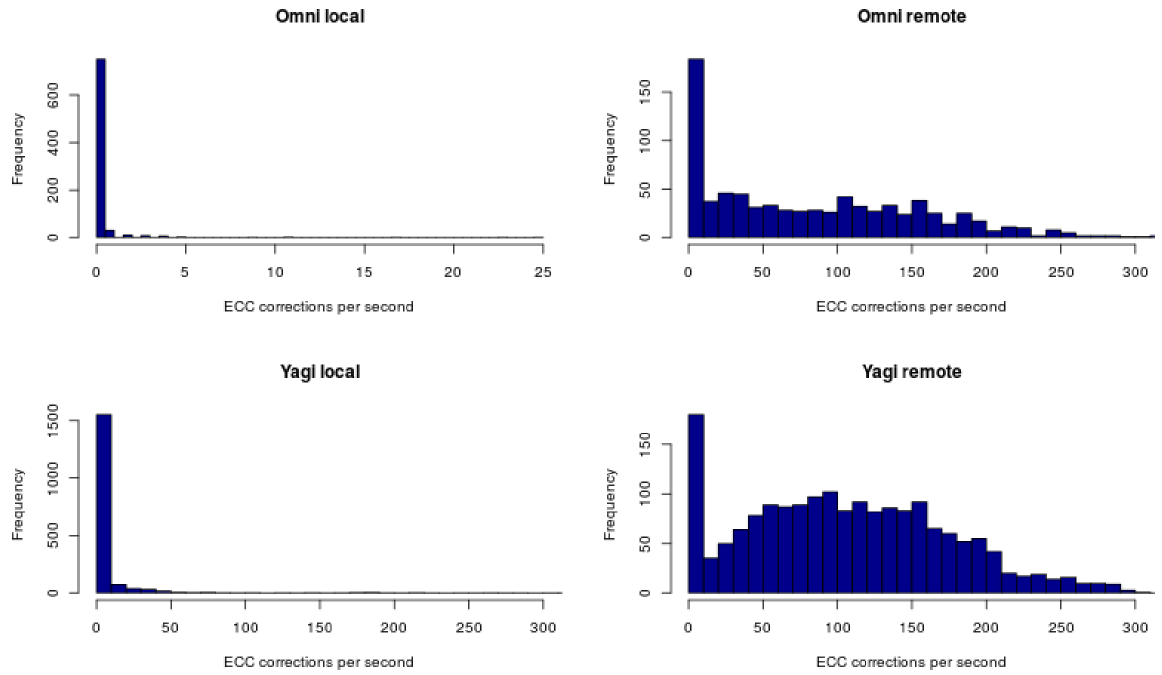

Figure 4: Error correction usage statistics

With error correction enabled, ECC is potentially applied to each 12 bits of user payload. TeRad employs a half-rate error correction scheme called the Golay code capable of correcting up to three bit errors in each 24 bit encoded word. Thus, with a sufficiently noisy received signal, a very large number of corrections may occur each second. Given a payload data rate measured in bits/second, the number of corrections available is one fourth of this figure (three corrections in the decoder for every 12 bits input to the encoder). Thus, at a nominal payload rate of 52 kbps, the theoretical maximum rate of ECC corrections per second is 13 thousand! Of course, this is only achievable if bit errors are perfectly evenly distributed, which is obviously not the real case. In practice, a few hundred corrections per second can be observed before the signal degrades to the point that there are errors left in the decoded words (the bit errors exceed the ECC recovery capacity) and thus fragment retries are necessitated.

Interestingly, local endpoints (the ones connected to the stationary antennas a few meters above ground level) need to perform a very small amount of ECC corrections compared to the numbers reported by the remote receiver on the aircraft. However, this is in accordance with the previous section's finding that on the ground, the number of lost datagrams in reception is much smaller than those lost in transmission (ie. those not received by the remote, airborne endpoint).

3.6 Precision of the link distance estimator

During the second phase of the measurement (flight 2) estimated link distances ('TeRad distance') were negotiated with the distance determined as GPS air distance by the ground team closely following the UAV by car ('Real distance'). Negotiated distances:

TeRad distance [km]	Real distance [km]	Error %
13.1	13.8	5.1
13.0	13.4	3.0
12.6	13.0	3.1
12.7	12.9	1.6
12.5	12.8	2.3
11.6	12.1	4.1
11.3	11.8	4.2
11.1	11.5	3.5
10.6	11.0	3.6

According to our findings, the radio systematically underestimates the link distance by a small margin. We believe that this is not due to some kind of measurement-specific effect that we have forgot to compensate for, rather a real systematic error in the link estimator.

The TeRad software estimates link distance based on measurements of the signal's propagation delay at well defined moments of the TeRad packet protocol. These measurements are exponentially averaged with a time constant of about 10 seconds, quite a long time. However, this is necessary because individual measurements' error is too large to be directly useful.

All in all, the rate of this underestimation seems to be around 3-5% compared to other methods deemed reliable and usable as a reference (GPS). With regard to the method of our implementation (measurement of propagation delay) and technical details thereof (hardware timer resolution of the microcontroller as well as constraints stemming from the TeRad software itself) we find this a remarkably fine result unequivocally suitable for its original purpose: to supply input to predicting or evaluating the link characteristics by giving a rough idea of the actual link distance.

4 Conclusion

This report demonstrated an in-field performance evaluation of the AMORES Robotics Telemetry Radio. The product was tested under real world conditions onboard an unmanned aircraft, in an environment very close to intended usage conditions. Diagnostic output was recorded and later analysed. General operation and the overall link service level provided by TeRad was found to be excellent.

5 Appendix

A route map of the experiment is shown in figure 5.

Figure 6 contains a photograph taken during the setup of our evaluation experiment. The dimensions of the two antenna stands clearly stand out compared to the other objects (the researchers carrying out the experiment and an automobile).

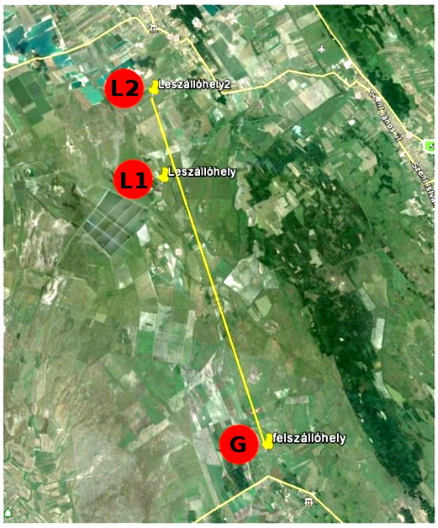

Figure 5: Route map of evaluation experiment

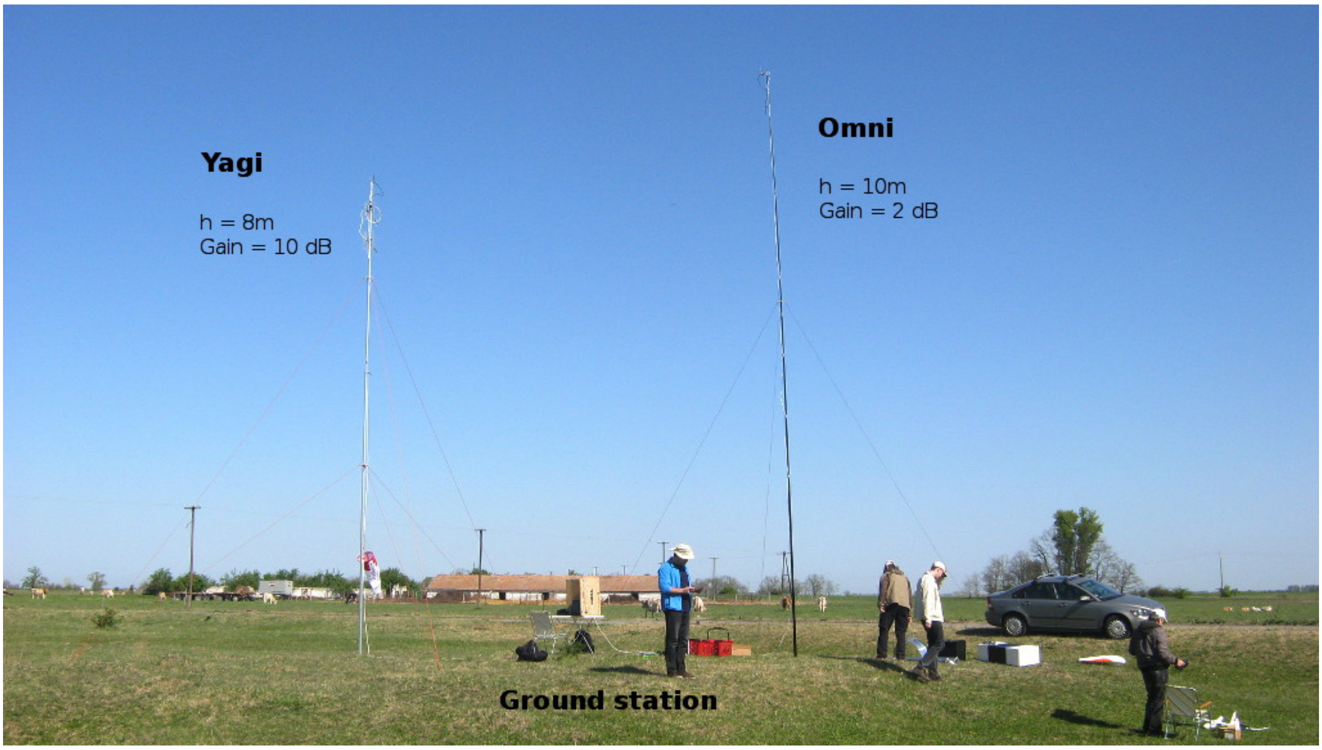

Figure 6: Photo of evaluation experiment (ground station with antennas)