RTK Corrections over a LoRa Network for Accurate Kayak Tracking

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***Abstract*—This work presents an RTK correction delivery system for kayak tracking that employs a fixed local RTK base station, eliminating the dependency on 4G connectivity to access the Centipede network.**
RTCM (*Radio Technical Commission for Maritime Services*) frames are transmitted from a shore-based reference station to a kayak-mounted rover via a 2.4 GHz LoRa network. The 2.4 GHz LoRa link provides sufficient throughput for RTCM messages (up to 100 kbps, depending on configuration) and reliable over-water communication ranges of up to 3 km line-of-sight.
The proposed architecture enables accurate, low-power, real-time kayak position estimation without the need for cellular coverage. Furthermore, the accuracy of the position estimates obtained using the local RTK base station is evaluated and compared to those achieved using corrections from the Centipede network.

I. Introduction

As of today (December 2025), there is no possibility for a visually impaired kayaker to compete at Paralympics or French competitions. Currently they can be in tandem or guided by voice when it comes to leisure or training. However in competition there is a strict rule resolving around the fact that you must be independent in your actions.
This paper presents the position estimation part of an automated system to assist visually impaired kayakers in maintaining their designated water lane during competitions. The system provides real-time audio feedback to indicate the kayaker's position relative to their lane. It is implemented for sprint competitions, where kayakers follow a straight course, facilitating accurate position estimation and timely audio guidance.

II. State-of-the-technologies for positioning

There are many technologies that can be used to estimate a position. They can be grouped into categories and subcategories (Figure 1). These technologies can be separated into two categories: **Indoor Positioning Systems** (IPS) and **Outdoor Positioning Systems** (OPS) [1].

Outdoor Positioning Systems (OPS) rely in most cases on **Global Navigation Satellite Systems** (GNSS). These navigation satellites can be grouped based on their affiliation: the United States' GPS, Russia's GLONASS, Europe's Galileo, and China's BeiDou. Typically, GNSS provides position accuracy under 5 meters in optimal conditions. But to achieve higher accuracy, **Real Time Kinematic** (RTK) uses an external fixed base to correct its position. Using dual-frequency L1 and L2 signals allows correction of ionospheric delays, significantly improving positioning accuracy, which is essential for high-precision RTK applications. Precise positioning is achieved once the coordinates of the fixed RTK base station have converged within a specified positional error threshold.
However, in urban areas, the effectiveness of OPS decreases rapidly, especially indoors. To address this, different Indoor Positioning Systems (IPS) were developed. The primary **wireless technologies** considered are Bluetooth Low Energy (BLE), Ultra-Wideband (UWB), Wi-Fi, and Zigbee. Signal exchange occurs between two modules, and distance is evaluated using three principles: **Received Signal Strength Indication** (RSSI), **Time of Arrival** (ToA), and **Angle of Arrival** (AoA). Their accuracy varies from a few centimeters to a few meters, despite having limited range.

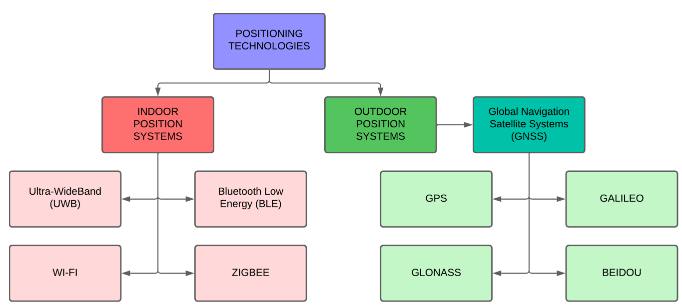

Fig. 1. Existing positioning technologies overview

III. State-of-the-art for positioning

In recent years, navigation research has increasingly focused on the fusion of **Global Navigation Satellite System** (GNSS) measurements with inertial sensor data to improve positioning robustness in challenging environments. **GPS-only** positioning, even when filtered using an Extended Kalman Filter (EKF), typically provides **meter-level** horizontal accuracy (1–5m) and several meters vertical (altitude) error (3–10m) under favorable satellite geometry, but suffers significant degradation during signal attenuation, multipath, or complete **satellite outages**. To mitigate these limitations, **inertial measurement units** (IMUs), composed of accelerometers and gyroscopes, are commonly integrated with GPS to provide **high-rate motion updates** (50–200Hz) and short-term navigation continuity. The EKF has become the standard framework for GPS/INS integration due to its ability to handle nonlinear system dynamics and measurement models while optimally fusing noisy sensor data. In this framework, the **inertial navigation system** (INS) propagated using IMU measurements updates the navigation state between GPS observations, while GPS measurements are used to correct the accumulated inertial drift. However, when low-cost MEMS IMUs such as those embedded in smartphones are employed, sensor biases and noise lead to rapid error growth during GPS outages, often reaching tens of meters in tens of seconds, limiting long-term accuracy. Recent work on kayak-based smartphone navigation demonstrated that both loosely coupled and tightly coupled GPS/INS EKF (Extended Kalman Filter) implementations degrade rapidly in the absence of GNSS updates, despite providing comparable performance under full satellite coverage. To address this challenge, **motion constraints** based on the kayak's specific movements were added to the EKF, which helped reduce INS error growth during GPS outages and improved positioning accuracy. These findings underline the critical role of EKF-based sensor fusion and application-specific motion constraints in enhancing the reliability of **low-cost GPS/INS systems**, such as those implemented on modern smartphones, which can achieve **meter-level accuracy** under open-sky conditions and maintain decimeter to meter-level accuracy during short GPS outages [2].

Another approach to improve GPS-based positioning is the use of **Kalman filtering on coordinate time series** [4]. In the cited study, two types of **motion models** were tested for the Kalman filter, the **identity model**, which treats the receiver's position as a random walk, and the **kinematic model**, which also includes velocity and predicts the next position based on it. The identity model was found to better describe the motion of the receiver antenna in their experiment. Filtering with either model improved position estimates, while smoothing further reduced errors, particularly when measurements contained outliers or missing data. These results show that Kalman filter-based time-series analysis can correct GPS positions and handle noisy or incomplete measurements, which is directly relevant to our work on refining RTK GPS measurements for lateral distance estimation.

Another recent approach to high-precision positioning is provided by the RTK project from Polytech'Grenoble, which implements a Real-Time Kinematic (RTK) system using an ESP32 microcontroller and Quectel LC29H EA/BS GNSS modules [3]. The system delivers centimeter level accuracy by applying RTCM corrections either via the ESP-NOW protocol with a local base station or through the Centipede network over WiFi. The base station automatically determines its position and sends corrections to the rover module, which outputs high-precision NMEA messages. In our work, we employ the same Quectel LC29H modules and systematically compare the positioning performance using corrections from a local base station versus those retrieved through the Centipede network, providing an evaluation of network-based versus local RTK corrections in dynamic conditions.

IV. Acquisition of corrected data

A. RTK principle

RTK (**Real-Time Kinematic**) GPS achieves **centimeter-level positioning** by exploiting the **carrier phase of GNSS signals**, in addition to **code pseudorange measurements**.
Differential GPS (DGPS) improves positioning accuracy by using a fixed base station to provide correction signals to a moving receiver. High-precision RTK GPS relies on carrier-phase measurements, where a carrier cycle represents one complete wavelength of the satellite's radio signal. **Carrier phase ambiguity** refers to the unknown integer number of full carrier signal wavelengths between the satellite and receiver at the start of observations. Carrier phase ambiguity is unknown because the receiver can only measure the fractional part of the carrier wave at the start. Counting all the full waves directly is impossible since the signal begins mid-wave and the receiver has no memory of the previous cycles. Initially, these ambiguities are **estimated as real-valued parameters in a float solution**, where both the baseline coordinates and ambiguities are jointly adjusted without enforcing their integer nature. To resolve the ambiguities, **integer least-squares estimation** and validation techniques are applied to separate the ambiguities from the baseline parameters and fix them to their correct integer values. While the float solution provides reasonable accuracy, it is limited by **ambiguity uncertainty**. When the ambiguities are successfully **resolved to their correct integer values**, a **fixed solution** is obtained, allowing the carrier phase measurements to behave like highly precise pseudorange observations and significantly improving positioning accuracy. This ambiguity must be estimated along with the receiver's coordinates [7].

A reference (base) receiver at a known position and a rover receiver simultaneously track the same satellites, typically using **dual-frequency signals** such as GPS L1 and L2. By differencing the carrier phase observations between satellites and receivers, common errors (e.g., satellite clock and atmospheric effects) are largely canceled while the remaining unknown integer number of carrier wavelengths (**integer ambiguities**) is estimated in real time. The resulting RTK solution can be either **float**, when the integer ambiguities are estimated as real-valued parameters and the position accuracy is typically at the decimeter level, or **fixed**, when the ambiguities are correctly resolved as integers, yielding stable centimeter-level accuracy.
In our case, we can either use existing open-source base from the Centipede network or create our own local base.

In GNSS, the primary carrier frequencies **L1 (1575.42 MHz) and L2 (1227.60 MHz)** correspond to wavelengths of approximately 19 cm and 24 cm, respectively. These relatively short wavelengths allow carrier phase measurements to achieve millimeter-level precision. Indeed, each cycle of the signal represents a smaller physical distance, so detecting a fraction of a cycle allows position changes to be measured with millimeter-level precision. Using two frequencies also helps correct **ionospheric delays**, since these errors vary with frequency. When combined with precise techniques, these measurements enable **survey-grade positioning**, meaning accuracies on the order of a few centimeters to millimeters.

To achieve survey-grade GNSS/GPS accuracy, different techniques are used (Figure 2): stop-and-go pauses briefly at points to record precise data, pseudokinematic collects continuous measurements while moving slowly, blending stationary and motion data, and rapid-static stays at each point for a few minutes to gather accurate observations before moving on. Each balances speed and accuracy depending on survey needs. GPS data can then be either postprocessed, with corrections applied after the survey, or processed in real time, allowing immediate use of high-precision positions. [5]

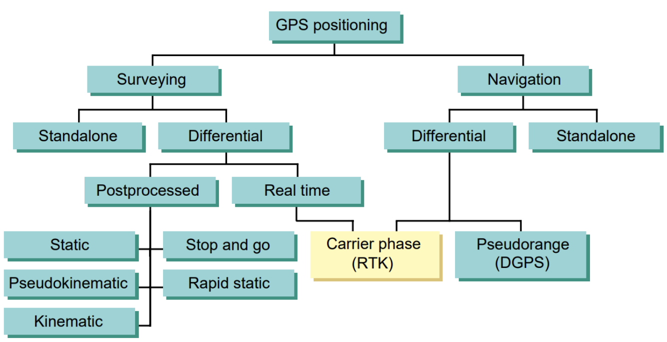

Fig. 2. GPS positioning applications [5]

B. Corrections from a CentipedeRTK network base

In France, their is an open-source bases network called CentipedeRTK. This network is financed by INRAE, National Research Institute for Agriculture, Food and Environment.
The CentipedeRTK network provides **free RTK correction data** through NTRIP (Networked Transport of RTCM via Internet Protocol) protocol. It consists of multiple GNSS reference stations distributed across France, which continuously collect GNSS data and transmit it to users in real time.
To access the CentipedeRTK network, users need to configure their GNSS receivers or software to connect to the NTRIP caster using the provided credentials. Once connected, the rover receiver receives the RTK correction data, which it uses to compute precise position solutions in real time.
To see the **available bases of the centipede network**:

https://map.centipede-rtk.org/index.php/view/map/

Despite the advantage of free access to RTK corrections, using the CentipedeRTK network may have some limitations. The **coverage area** may not be as extensive as commercial RTK services, and the availability and reliability of the correction data may vary depending on the network infrastructure and maintenance. Additionally, users may need to ensure that their GNSS receivers are compatible with the NTRIP protocol and can properly interpret the correction data provided by the CentipedeRTK network.
In our case, the main disadvantage is the need of an internet connection to get the corrections from the CentipedeRTK network. For reasons of reliability and cost, we chose not to implement WiFi connectivity in our system.
Implementing our own base station addresses these limitations: the base is physically closer to the rover, which reduces signal latency and improves the overall accuracy of the corrections. Moreover, the base and rover experience **identical environmental** and meteorological conditions, which further **enhances correction quality**. Finally, having a dedicated base allows for full control over the correction settings, update rate, and system reliability, ensuring consistent performance in our specific operational environment.

C. Implementation of a fix local correction base

The solution presented in this paper consist in the implmentation of our own RTK base station on the side of the racing course. This base station is connected to a fixed GNSS antenna placed in a known position. The base station computes the RTK corrections from the GNSS data received by the antenna and transmit them to the rover module on the kayak through a **long-range radio link (LoRa 2.4GHz)**.

The base station outputs **RTCM 10403.3 (RTCM 3.3) messages** to provide the rover with real-time corrections. The messages relevant for RTK positioning include:

- **1005: Stationary RTK Reference Station ARP**: defines the exact coordinates of the base antenna. (22 bytes)
- **Ephemerides:** GPS (1019), GLONASS (1020), BDS (1042), QZSS (1044), Galileo (1046). Satellite positions for accurate navigation. (100-300 bytes each, usually sent at 1 Hz)
- **MSM4 / MSM7:** Multi-Signal Messages for observations (GPS 1074/1077, GLONASS 1084/1087, Galileo 1094/1097, QZSS 1114/1117). They contains pseudorange, carrier phase, and multi-frequency data used for RTK computations. MSM4 is minimal, MSM7 contains full multi-frequency data. (100-200 bytes per message, sent at 10 Hz for real-time rover updates)

With an update rate of 10 Hz, the typical throughput of these RTCM messages is approximately:

$$200\,\text{bytes} \times 10\,\text{Hz} \approx 16\,\text{kbps},$$

which sets a minimum requirement for the communication link.

We selected LoRa 2.4 GHz over other options for transmitting RTCM 10403.3 corrections due to the combination of **sufficient data rate and practical range** for our application.

LoRa 868 MHz is only partially suitable for 10 Hz RTCM messages because its lower data rate (5-11 kbps) may require **fragmentation**, potentially introducing latency.

ESP-NOW 2.4 GHz is not suitable for our application because its maximum practical range (200-300 m) is too short for the racing course, despite its high burst data rate.

TABLE I
COMPARISON OF COMMUNICATION LINKS FOR RTCM 10403.3 TRANSMISSION

Link	Max Data Rate	Max Range
LoRa 2.4 GHz	50–300 kbps	0.5–2 km
LoRa 868 MHz	5–11 kbps	2–5 km
ESP-NOW 2.4 GHz	1–2 Mbps (burst)	200–300 m

The architecture of the entire system is shown in Figure 3. The base station consists of a GNSS antenna connected to a LC29H-BS board transmiting correction through UART to a LILYGO T3 S3 board that computes the RTK corrections. The LILYGO T3 S3 board include a LoRa transmitter/receiver (SX1280 LoRa 2.4GHz) that sends the corrections to a LoRa receiver on the kayak.
On the kayak, the LC29H-EA rover module receives the RTK corrections from the LoRa receiver (LILYGO T3 S3) through UART and applies them to compute the corrected position in real time.

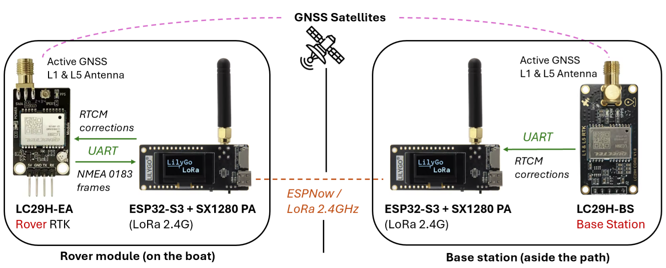

Fig. 3. Architecture of the entire system

This solution allows us to have a reliable and cost-effective RTK positioning system without the need for an internet connection on the kayak.

V. PROCESSING OF LOCATION DATA

Now that we are receiving the corrected location data, we must **process** them in order to **estimate on which side** of the waterline the kayak is located.
The LC29H-EA rover module returns the GPS data in **NMEA 0183 frame format**. An NMEA frame is a standardized ASCII sentence that starts with '$', contains comma-separated fields conveying GPS or sensor data, and ends with a '*' followed by a checksum and a carriage return/line feed.
From those data acquired in UART, only the GGA frame will interest us. Time, position, and fix related data. GNGGA stands for **Global Navigation Satellite System**, and its data can combine multiple constellations such as GPS, GLONASS, and Galileo. This multi-constellation support, introduced in **NMEA 4.x**, allows for higher accuracy and more satellites in view compared to GPS-only GPGGA sentences.

The pattern of a **GNGGA** NMEA sentence is the following :

***$GNGGA**, UTC hour, **Lat**, N/S, **Lon**, E/W, Fix quality, Nb Satellites, HDOP, Altitude, Unity, Geoid gap, Unity, DGPS Age, DGPS station ID, Checksum*

From that frame we only extract the latitude and the longitude.
For every waterline, **three fixed coordinates** must be known: **A**, a point of the center line on the starting line; **C**, a point of the center line on the finish line; and **B**, on the starting line at the left border of the waterline (Figure 4). These three points must define an orthogonal reference frame. P_n and P_{n+1} are the coordinates of the kayak at times n and $n+1$.

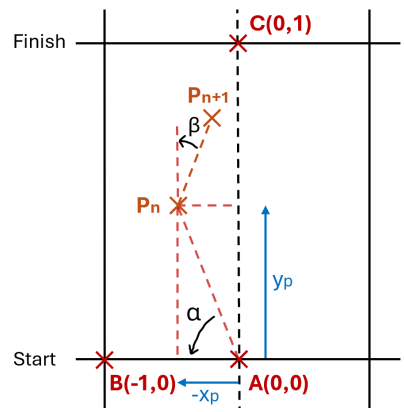

Fig. 4. Points on the waterline

Lets x_p and y_p the respective projections of point P_n on axes (BA) and (AC) :

$$\begin{cases} x_p = -|AP|\cos(\alpha) \\ y_p = |AP|\sin(\alpha) \end{cases}$$

The calculation of the angle α is done using the **law of cosines** :

$$\cos(\alpha) = \frac{|BP|^2 - |AP|^2 - |BA|^2}{-2|AP||BP|}$$

A positive $\cos(\alpha)$ corresponds to an acute angle between (AP) and (AB), meaning the point P is on the left side of the center line; a negative $\cos(\alpha)$ corresponds to an obtuse angle, placing P on the right side.

The **Haversine formula** is used to compute the absolute distance in meters between two points from their latitude and longitude coordinates. It calculates the **great-circle distance between two points on a sphere**, such as the Earth. Given two points $(\text{lat}_1, \text{lon}_1)$ and $(\text{lat}_2, \text{lon}_2)$, the distance d is obtained as follows:

$$\begin{cases} \Delta\text{lat} &= \text{lat}_2 - \text{lat}_1 \\ \Delta\text{lon} &= \text{lon}_2 - \text{lon}_1 \end{cases}$$

$$a = \sin^2\left(\frac{\Delta\text{lat}}{2}\right) + \cos(\text{lat}_1)\cdot\cos(\text{lat}_2)\cdot\sin^2\left(\frac{\Delta\text{lon}}{2}\right)$$
$$c = 2\cdot\arctan 2(\sqrt{a}, \sqrt{1-a})$$
$$d = R\cdot c$$

where R is the Earth's mean radius (approximately 6371000 meters), and latitudes and longitudes are expressed in radians.

The function $\arctan 2(y, x)$ returns the arctangent of the coordinates (x, y) as an angle expressed in radians, taking into account the correct quadrant of the point. In contrast, the standard $\arctan(z)$ function takes a single argument $z = y/x$ and returns an angle in the range $[-\pi/2, \pi/2]$, which does not distinguish the quadrant.

The orientation of the kayak is an interesting parameter to consider in addition of its relative position. To compute it we simply need the position of the new point P_{n+1} inside the base defined by (AB,AC) as well as the position of the previous point P_n :

$$\begin{cases} \Delta x = x_{P_{n+1}} - x_{P_n} \\ \Delta y = y_{P_{n+1}} - y_{P_n} \end{cases}$$

$$\beta = \arctan\left(\frac{\Delta x}{\Delta y}\right)$$

Therefore, under the assumption that (AB) and (AC) are orthogonal, only points A and B are required in order to estimate the position as well as the orientation of the boat. Provided that the coordinates of points A and B are correctly recorded, there is a risk of considering a line (AC) that is not parallel to the waterline. To increase accuracy when recording the points, B can be chosen as far away from A as possible. The ratio $x_p/|AB|$ provides information about the kayaker's position relative to the waterline. Point C might be usefull only if we want to signal the remaining distance to cover by the athlete. If not only both A and B points are necessary for the race.

VI. Results

A. CentipedeRTK network base results

The CentipedeRTK network base station used is located in the city of Queven (France) at the following coordinates:

- Latitude: 47.84321899°
- Longitude: -3.41345172°
- Altitude: 111.769 m

The data from this base station is transmitted in real-time via the NTRIP protocol. The rover receives these corrections and applies them to its own GNSS measurements to compute accurate positions. The rover's position is determined using RTK algorithms that combine the base station data with the rover's raw GNSS observations.

The accuracy and reliability of the RTK solution provided by the CentipedeRTK network are assessed by analyzing the rover's logged positions.
The following figure illustrates the **relative error of the rover along a straight-line trajectory** as a function of its position, using the CentipedeRTK network base station. The error shown is the difference between the measured and expected positions along the trajectory.

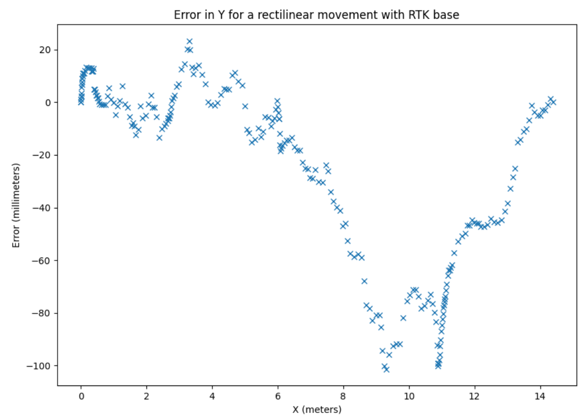

Fig. 5. Rover error over its position using CentipedeRTK network base station

As shown in Figure 5, the **rover's relative error** remains low, with a **mean value of approximately 2.9 cm** along the trajectory. The **maximum observed error reaches 10.1 cm** at certain points, indicating occasional deviations from the expected position. Overall, the CentipedeRTK network base station provides a reliable RTK solution for the rover, with most relative errors remaining within a few centimeters on a straight-line trajectory.

B. Fix local base results

For the fix local base station, the rover's position is determined using **corrections from a nearby static GNSS receiver** set up as a local base station. The local base station's coordinates are known and used to **compute differential corrections** for the rover's GNSS measurements.
The accuracy of the RTK solution provided by the local base station is evaluated by analyzing the rover's logged positions. The following figure illustrates the **relative error of the rover along a straight-line trajectory** as a function of its position, when using the local base station. The error shown is the difference between the measured and expected positions along the trajectory.

As depicted in Figure 6, the rover's error remains consistently low, with a **mean error of approximately 1.7 cm** throughout the trajectory. The **maximum error reaches up to 7.6 cm** at certain points, indicating occasional deviations from the expected position. Overall, the fix local base station provides a reliable RTK solution for the rover, with most relative errors remaining within a few centimeters

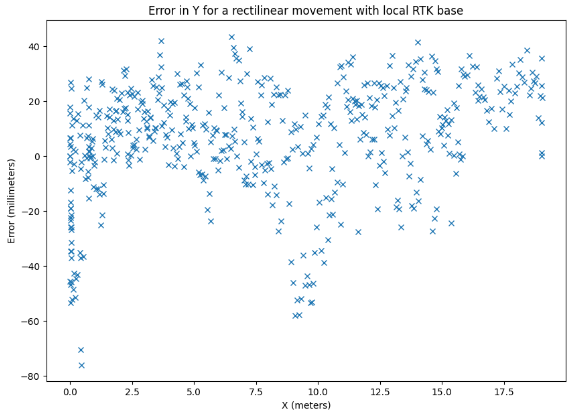

Fig. 6. Rover error over its position using fix local base station

on a straight-line trajectory.

C. *Topographic reference mark results and absolute positioning*

Topographic reference marks (also known as **geodetic** or **survey markers**) are permanently materialized points installed in the field to provide reliable and stable spatial references for geodetic applications. Each reference mark is associated with precisely determined coordinates within a national geodetic reference system (e.g., RGF93 in France).

In France, official **topographic and geodetic reference marks** maintained by the Institut national de l'information géographique et forestière (IGN) are publicly documented. Their descriptive sheets, including coordinates, monumentation details, photographs, and status information, can be consulted through the IGN geodetic database available online at:

https://fiches-geodesie.ign.fr/fiches/index.php?module=e&action=visugeod

To know the **absolute position of the rover**, we could use these topographic reference marks as fixed points with known coordinates. By measuring the rover's position when placed on these marks, we can compare the rover's computed position with the known coordinates of the reference marks to **assess the absolute accuracy** of the rover's positioning system.
However, during our tests, we encountered difficulties in accurately positioning the rover on these topographic reference marks due to the movement of the tectonic plate in this region. This movement can lead to discrepancies between the known coordinates of the reference marks and their actual positions at the time of measurement.
The last measurement on the topographic reference mark was made in 1986, and since then, the tectonic plate has shifted, causing a deviation of 2-3 centimeters per year [6]. Over the span of nearly four decades, this cumulative shift can result in significant discrepancies between the recorded coordinates and the rover's actual position when placed on these marks. That is why we could not use these topographic reference marks to determine the absolute position of the rover accurately.

VII. Conclusion

The use of a **local correction base** significantly improved positioning accuracy along a straight-line trajectory. The mean error was reduced by a factor of 1.7 compared to the use of a **CentipedeRTK base**, highlighting the benefit of localized reference stations for high-precision applications.
Although the RTK GPS measurements already provide a high level of accuracy, the results could be further improved by applying a **Kalman filter** to **smooth the estimated position** or the **derived lateral distance**. Given the quasi-linear system dynamics and the limited deviations observed along a mostly planar trajectory, a **standard linear Kalman filter** appears to be well suited for this application. Such an approach would allow for noise reduction and improved positional consistency while maintaining low computational complexity, making it a promising perspective for enhancing the robustness of lateral distance estimation in future work.

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