SUB-MILLIMETRIC FIELD MEASUREMENTS OVER KILOMETRES USING ARPENT TWO-WAVELENGTH ADM

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Abstract

Cnam has developed Arpent, a two-wavelength ADM where the distances do not depend on the air refractive index, but only on the dispersion. By simultaneously measuring two optical path lengths at two different wavelengths, it is no longer necessary to determine the air temperature and pressure. Arpent measures distances consistent with the SI-metre definition and achieves uncertainties better than 1 mm over 8 km (k=1), which can be of great interest for the surveying of large structures such as particle accelerators. This article describes the operating principle and performance of Arpent. Firstly, compensation for changes in the air refractive index when measuring a fixed distance of 2.6 km or 5.4 km over several days showed standard deviations lower than 0.3 mm. Secondly, distances were compared with those of the GNSS-based distance meter (GBDM+) developed by UPV, for nine baselines ranging from 1.0 km to 6.5 km and located at two reference sites: EURO5000 and CERN. The distances provided by Arpent and GBDM+ proved compatible within their uncertainties (k=1) for seven baselines, and the differences had a standard deviation of 1.8 mm. Finally, Arpent was tested over 8 km. The two-wavelength ADM and GBDM+ will soon be used to transfer absolute scale to the new INTA1000 calibration baseline at the Spanish National Institute of Aerospace Technology (INTA).

MOTIVATION AND ARPENT PRINCIPLE

There is a growing demand for distance measurements over several kilometres and with a sub-millimetric accuracy. This includes the possible construction of the Future Circular Collider (FCC) at CERN, the determination of local ties at geodetic observatories, and the monitoring of large structures such as calibration baselines or dams. Optical telemetry can meet these needs if it solves the problem of determining the air refractive index n. The latter is generally calculated using the Ciddor formula [1, 2], which is recommended by the International Association of Geodesy (IAG) and requires the measurements of the following atmospheric parameters: the air temperature T, the pressure p, the partial pressure of water vapour p_ω, and the CO_2 content x_{CO2}.

In the past, absolute distance metres not requiring the knowledge of air temperature and atmospheric pressure were developed, for example the well-known Kern Terrameter LDM-2 used at CERN in the 1980s [3]. Its principle is based on simultaneous measurements of two optical path lengths, D_1 and D_2, at two different wavelengths, λ_1 and λ_2. The air-index compensated distance L is then equal to:

$$L = D_1 - \frac{n(\lambda_1, T, p, x, p_\omega) - 1}{n(\lambda_2, \ldots) - n(\lambda_1, \ldots)} \times (D_2 - D_1)$$
$$= \frac{K(\lambda_1)D_2 - K(\lambda_2)D_1}{K(\lambda_1) - K(\lambda_2) + p_\omega \times \big(g(\lambda_1)K(\lambda_2) - g(\lambda_2)K(\lambda_1)\big)}$$

where $K(\lambda)$ and $g(\lambda)$ are, respectively, the dispersion and humidity terms defined in the Edlén formula and similar updated formulae [4]. The term $(n(\lambda_1)-1)\,/\,(n(\lambda_2)-n(\lambda_1))$ is called the factor A and is significantly less sensitive to atmospheric parameters than the air refractive index. In the end, only the air humidity must be measured, i.e. p_ω.

The two-wavelength ADMs used until the late 1980s are no longer commercially available and those manufactured are generally no longer operational. That is why new developments are underway, and why we have designed a prototype based on modern components and named Arpent. It operates at 780 nm and 1560 nm for a factor A of about 48. Our prototype, presented in detail in [5] and visible in Fig. 1, measures optical path lengths consistent with the SI-definition of the metre and achieves uncertainties better than 1 mm up to 8 km (k=1).

It should be noted that even over short distances of a few hundred metres, such a system is also of great interest because it eliminates the need to measure air temperature.

The principle of our two-wavelength ADM is a classic one. The two beams, spatially superimposed so that they propagate along the same path, are sent to a retroreflective target and reflected back to the instrument. The optical beams emitted are both modulated in intensity by a sine wave of frequency 5 GHz. Thus, to determine the two optical path lengths D_1 and D_2, the phase shifts (of the modulations) between the emitted beams and the return ones after round-trip up to the distant target are measured. In our system, the wavelength at 1560 nm is generated by a laser diode, while the second wavelength at 780 nm is obtained by frequency doubling in a non-linear crystal.

The approach adopted is the simplest possible, but it introduces a cyclic error due to crosstalks (i.e. spurious noises) at each wavelength, and therefore on the compensated distance. This cyclic error is the one that contributes most to the final uncertainty: its amplitude defines the level of uncertainty in the air-index compensated distance, which can be estimated from the received electrical power

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levels of the modulations (i.e. the signal-to-crosstalk ratios) and the measured distance. The received powers must be higher than -15 dBm to keep the amplitude of the cyclic error of the air-index compensated distance below 1.4 mm (i.e. in the worst case, uncertainty of 1 mm at k=1, considering an arcsine distribution for the cyclic error), and ideally higher than -5 dBm to keep it negligible with an amplitude below 0.45 mm. In practice, the uncertainty typically ranges from 0.3 mm to 0.7 mm at k=1 up to 8 km.

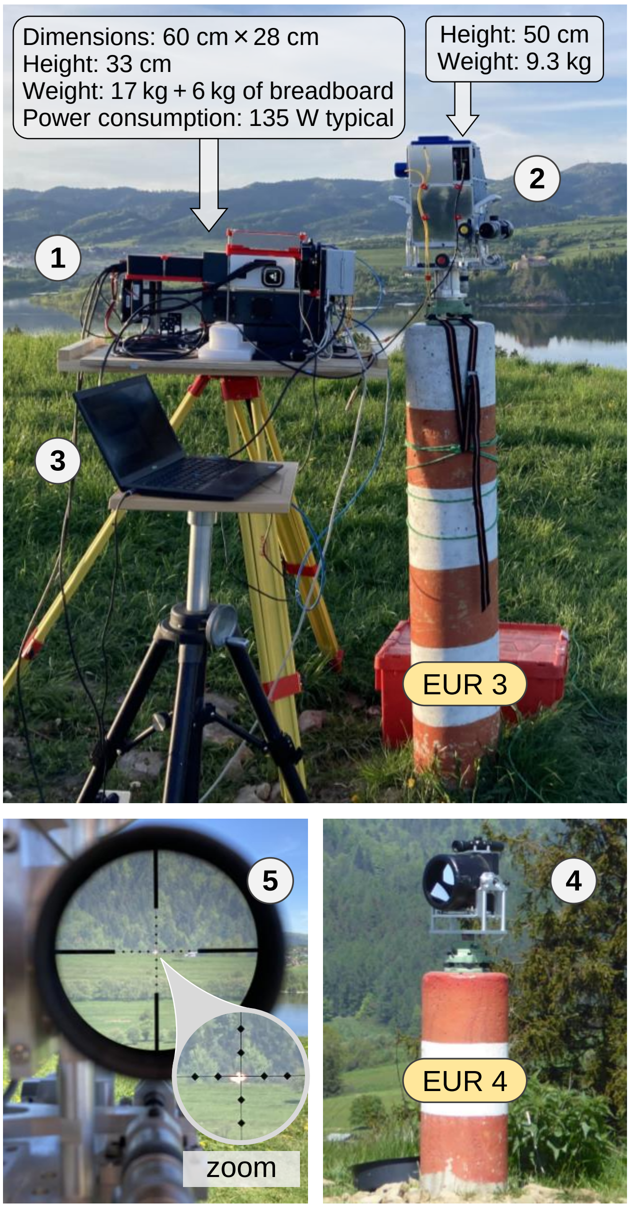

Figure 1: Arpent (top) and its target (below right) during the measurement of the EUR3-EUR4 baseline (3.1 km) in Poland. (1) The fibre-guided ADM with its fibre outputs, one per wavelength. (2) The optical head for collimation of the beams, their spatial superposition, and their alignment towards the distant target. (3) Computer for monitoring of the measurement parameters and data processing. (4) Hollow corner cube of 127 mm aperture mounted on a gimbal mechanism as the optical head. (5) View through the sighting scope of the optical head (780 nm beam spot visible).

REFRACTIVE-INDEX COMPENSATION

To demonstrate the benefit of such a system, we compared two different approaches for the measurement of fixed distances over 2.6 km (Plateau de Calern, France) and 5.4 km (between Paris and Meudon, France): **1.** conventional distance measurement at 780 nm with recording of the atmospheric parameters on the instrument side, pressure correction for the difference in altitude between the baseline endpoints, then correction for the air refractive index; **2.** air-index compensated distance measurement at 780 nm and 1560 nm.

The results are presented in Fig. 2 for received power higher than -5 dBm, i.e. a cyclic error negligible. Over 2.6 km, the temperature and pressure variations observed over three successive days were 8 °C and 8 hPa, while over 5.4 km, they were 10 °C and 17 hPa over 6 days.

With the conventional approach, we observe peak-to-peak drifts of 10.3 mm and 36.6 mm for 2.6 km and 5.4 km, respectively. The corresponding standard deviations are 1.9 mm and 5.1 mm. On the other hand, the two-wavelength telemetry shows in both cases peak-to-peak drifts close to 2 mm and standard deviations of 0.3 mm, which demonstrates the good compensation of changes in air refractive index.

The deviations of the conventional approach from the average distance obtained by the two-wavelength ADM can be explained by measured temperatures up to 7.2 °C higher than the average temperatures along the line of sight. Ideally, temperature should be measured on both sides as its contribution to the air refractive index is high (0.95 mm/km per °C).

ABSOLUTE DISTANCE MEASUREMENT

The system developed was also compared with the improved GNSS-based distance meter (GBDM+) developed by UPV and presented in [6]. Unlike the ADM, this technique, which employs GNSS signals collected by using individually calibrated antennas, does not require inter-visibility and the resulting distance scale relies on the accuracy of the precise ephemeris and ultimately on the International Terrestrial Reference Frame (ITRF) [7]. It uses a functional model that directly provides the baseline distance with its uncertainty as propagated from the error sources in the satellite-receiver line of sight.

A first comparison was carried out on the EURO5000 reference baseline in May 2022 (Pieniny Klippen Belt in Poland) and a second one on the CERN geodetic network in July 2022 (near Geneva, Switzerland) [8, 9]. This represents a set of nine measured distances ranging from 1.0 km to 6.5 km. It should be noted that the uncertainty of the two-wavelength system was degraded during the measurement campaign on the EURO5000 baseline due to a technical problem: optical attenuators introduced variable delays on the phase shifts measured at each wavelength. The uncertainty was therefore extended to 1.2 mm at k=1. Following this campaign, this problem was resolved, and for the measurements made at CERN, the uncertainties returned to their expected values.

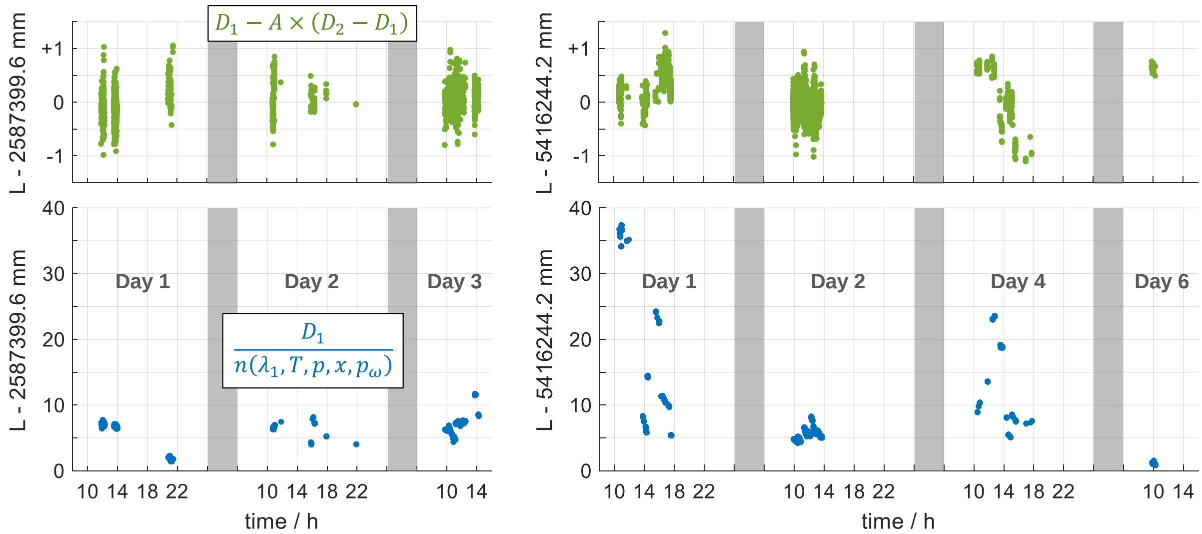

Figure 2: Comparison of the two different approaches over several days, with air-refractive index compensation at the top (green) and with conventional approach at the bottom (blue), for 2.6 km (left) and 5.4 km (right).

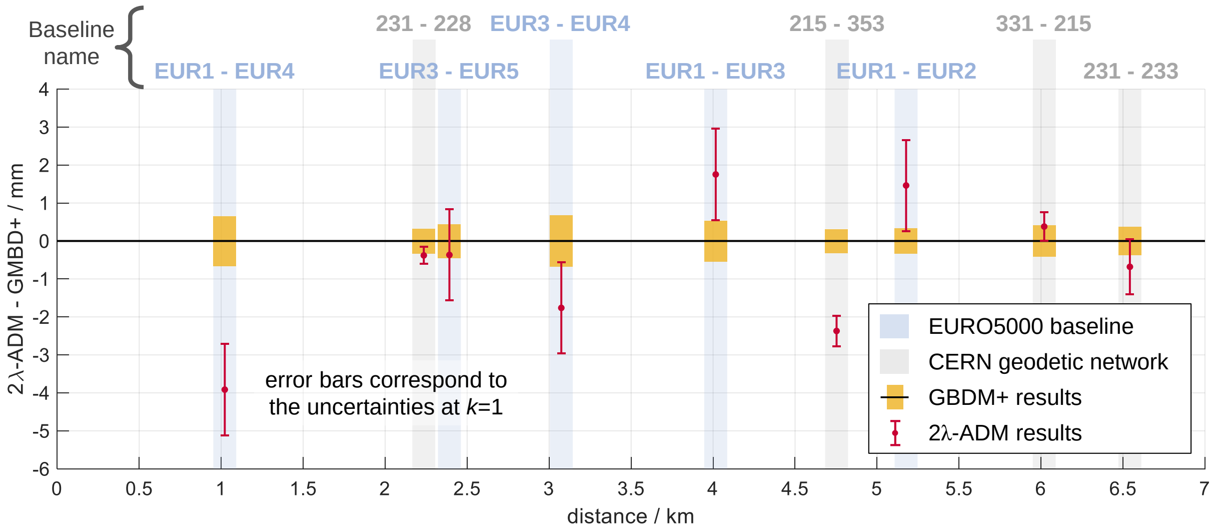

Figure 3: Comparison of the two-wavelength ADM with the GBDM+. The GBDM+ values are centred on zero so that the displayed values of the ADM correspond to the difference between the two systems. The measurement uncertainties u_m at k=1 are depicted by symmetrical error bars for Arpent and by symmetrical yellow box for GBDM+ ($\pm u_m$).

The measurement campaign at the EURO5000 reference site was carried out over 4 days. Over the measurement period, the temperature varied by 17 °C (from 9.5 °C to 26.5 °C), the pressure by 27 hPa (from 929 hPa to 956 hPa), and the partial pressure of water vapour by 1 kPa (from 395 Pa to 1420 Pa). Only the baseline of 4.0 km was measured from both sides (instrument in EUR1 on day 2 and in EUR3 on day 3), with the measurements of each day being compatible within their standard deviation. The measurement campaign at the CERN geodetic network was carried out over 5 days. The temperature varied also by 17 °C (from 15 °C to 32 °C), the pressure by 35 hPa (from 936 hPa to 971 hPa), and the partial pressure of water vapour by 1 kPa (from 1 kPa to 2 kPa). The baselines of 4.8 km and 6.0 km were measured from both sides, and again the individual measurements were compatible within their standard deviation.

Fig. 3 shows the results of the comparison. The distances estimated by the two systems are compatible within their uncertainties at k=1 in 7 cases over 9, and their differences show a standard deviation of 1.8 mm. No scale error is visible. However, two baselines showed significant discrepancies: EUR1-EUR4 (1.0 km) and 215-353 (4.7 km). First, the two measurements, ADM and GBDM+, were carried out one week apart, and pillars can be subject to possible movements in between, especially pillar 215 at CERN that is located on a building roof. For the baseline of 1.0 km, the error comes mainly from the ADM due to the additional delays introduced by optical attenuators (problem since solved), while for the baseline of 4.7 km, the error probably comes from the GBDM+ because the results depended on the processing time more than expected (see details in [9]).

MAXIMAL RANGE

Finally, a measurement over about 8 km was tested to check if such a distance could be achieved. This test was carried out during the EURO5000 campaign in May 2022, from EUR3 to the lookout tower on Luban. The result is shown in Fig. 4: the 20-minute recordings show that signals higher than -15 dBm for both wavelengths were obtained (points in green), which is a sufficient signal level for a distance uncertainty of less than 1 mm (k=1). 8 km seems to be the maximal range of Arpent. On these recordings, we can also observe that distance deviations increase highly with low levels of received powers.

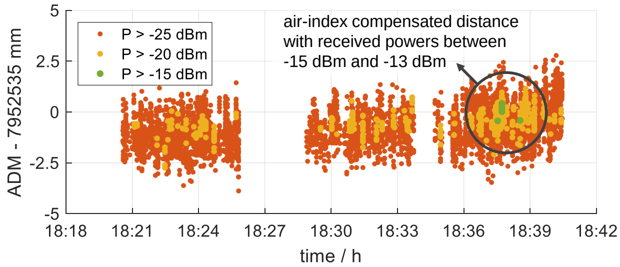

Figure 4: Time series of distance measurements over 8 km as a function of the received powers.

CONCLUSION

A two-wavelength ADM has been developed. It is relatively compact, easily deployable in the field, and can provide measurements in a few minutes, whereas it takes hours to integrate GNSS signals. However, a direct intervisibility between the instrument and its retroreflector, i.e. between the two baseline ends, is required.

Field measurements have shown compensation for temperature and pressure along beam's paths of 2.6 km and 5.4 km with standard deviations of 0.3 mm. In addition, absolute distance measurements from 1.0 km to 6.5 km were carried at two reference sites, EURO5000 and CERN. These are consistent with measurements obtained using the GBDM+ developed by UPV, with differences showing a standard deviation of 1.8 mm. In the latter case, two significant discrepancies were observed, but these can be explained.

In the future we plan to carry out additional measurements over a large number of distances and diverse atmospheric conditions to confirm the initial results obtained as part of the European research project GeoMetre [10]. This will be done in part through the Spanish research project GNSS-Metrology. Moreover, the two-wavelength ADM and GBDM+ will soon be used to transfer absolute scale to the new INTA1000 calibration baseline at the Spanish National Institute of Aerospace Technology (INTA).

Finally, the uncertainty budget for the air-index compensated distance L assumed that the physical model was perfectly known, i.e. without error. It is based on the dispersion and humidity terms defined in the Edlén formula and similar updated formulae. A detailed study has to be carried out to account for possible errors in these terms. It should be noted that the results presented in this article are based on the Voronin and Zheltikov equation [11].

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