A new approach to long distance EDM: Using intermode beating of broadband ultrashort laser pulses

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Abstract

The accuracy of Electro-Optical Distance Measurement (EDM) of high-end total stations working with cooperative targets over longer distances is limited to a few ppm or worse due to insufficient knowledge of the refractive index of air along the signal propagation path. In cases where the local scale parameter approach is not applicable, the deviations due to refraction can only be mitigated by exploiting the dispersion of the atmosphere. The use of simultaneous observations at two wavelengths to estimate the integral refractive index along the propagation path was proposed and demonstrated some decades ago. However, the widespread commercial application of the multiwavelength EDM solution had been impeded by considerable technical complexity and it had been abandoned in favor of differential, carrier-phase-based GNSS measurements when these had become available.

Recently, the approach has gained attention again because of new application needs and availability of modern optoelectronics and special light sources. One promising approach is exploiting the intermode beats generated by a mode-locked femtosecond-laser (fs-laser) representing high-quality and high-frequency signals suitable for distance estimation. This non-interferometric approach has already been demonstrated as a robust alternative to standard long-distance EDM methods. We extend this idea to intermode beating of wideband sources obtained by spectral broadening of a fs-laser establishing a technological basis for hyperspectral phase-based EDM.

We present the basic principles of the technology and discuss the anticipated applications to both (i) high-accuracy long-distance EDM with cooperative targets, and (ii) contact-less extraction of information on surface material and properties in addition to surface geometry from laser scanning. We also present results from experiments using a fs-laser broadened by supercontinuum generation producing light between 550 nm and 1050 nm. Our displacement measurements on a short-distance set-up show that the internal coherence and noise of the supercontinuum are adequate for achieving precisions at the level of a few tens of µm, which is in turn good enough to allow for compensation of atmospheric effects via multiwavelength measurement.

Key words: EDM, fs-laser, intermode beating, multiwavelength EDM, hyperspectral EDM, refractivity compensation

1 INTRODUCTION

EDM is an essential technology for surveying and large-scale metrology. The same working principle is used by a variety of different instruments, i.e., some form of non-interferometric delay measurement of an optical signal propagating from the instrument to a target and back. In the context of surveying, these are total stations providing EDM with cooperative targets like corner cube reflectors, and laser scanners and total stations providing reflectorless EDM with object surfaces acting as reflectors. Cooperative targets guarantee that a high portion of the optical energy is recovered by the instrument after reflection and that the point of reflection is clearly defined. This enables longer range, higher accuracy and less dependence of measurement noise on the distance than obtained using reflectorless measurements.

Modern high-end EDM systems with cooperative targets can measure distances up to a few km and potentially achieve standard deviations better than 1 mm. Achieving also accuracies on that level would require knowledge of the integral refractive index of air along the beam path. While sufficiently accurate equations for calculating the refractive index as a function of wavelength, density and composition of the air have long been available [Barrell & Sears, 1939; Ciddor, 1996; Ciddor & Hill, 1999; Edlén, 1953], meteorological observations can rarely be made along the whole propagation path with enough accuracy, temporal and spatial resolution [Brunner & Rüeger, 1992; Pollinger et al., 2012]. Even if meteorological observations are taken at both end points of the distance, errors of 5 ppm or more can be left after application of the corresponding atmospheric correction, because the meteorological measurements are taken close to the ground, within the highly variable surface layer of the atmosphere, and may not be representative for the integral along the signal path if the latter is not short and parallel to the surface [Brunner & Rüeger, 1992]. The refractivity error is a dominant error contribution for current EDM technology with ranges exceeding a few hundred meters. It often impedes EDM-based monitoring with mm or sub-mm level accuracy which would otherwise be technologically feasible. If the lines-of-sight between the instrument and the targets are equal in terms of refractivity for sets of targets and if a couple of targets per set are stable, the local scale parameter approach [Brunner & Rüeger, 1992] can be used for successful and cost-effective mitigation of atmospheric effects on EDM. However, for many applications in e.g. mountainous or underground environment, this is not the case.

The atmosphere is dispersive for optical radiation, i.e., the refractive index depends on the wavelength. The combination of delay measurements at different wavelengths can thus be used to derive refractivity-compensated distance estimations which are hardly affected by the atmospheric conditions. This method was first proposed more than 50 years ago by [Bender & Owens, 1965] who provided the theoretical solution for two wavelengths in dry air. Some practical implementations were attempted in the following years with varying degrees of success [Bouricius & Earnshaw, 1974; Earnshaw & Hernandez, 1972; Levine, 1984; Slater & Huggett, 1976]. These investigations proved the feasibility of the method, which ultimately led to the development of the Terrameter [Huggett, 1981] in the early 1980s. The Terrameter has been the only refractivity-compensated dual-wavelength EDM instrument ever manufactured for commercialization, although at a very limited scale. Reports on its application to the geodetic control network for the alignment of the Large Electron-Positron Collider at CERN state that an accuracy of 0.1 ppm was effectively achieved over some km under favorable atmospheric conditions [Gervaise, 1983]. It required, however, constant specialized supervision and extensive on-site adaptations for every location [Gervaise, 1983]. When high-accuracy carrier-phase differential GPS techniques became available, they quickly emerged as a much more convenient solution for measuring distances over more than a few kilometers, and the practical necessity for further research on and development of multiwavelength EDM disappeared.

Nowadays, increasing demands in applications such as geomonitoring, urban monitoring and construction of large underground facilities call again for highly accurate distance measurements with ranges from a few hundred meters to a few kilometers and in contexts where GNSS is not applicable, e.g. [Frukacz et al., 2017]. EDM with integral atmospheric compensation appears again as a suitable technology to fulfill such requirements, reviving the interest in developing two-color instruments [Guillory et al., 2016] and multiwavelength solutions. Due to the relatively low dispersion of the atmosphere in the visible and near infrared regions of the spectrum, the differential path delay between the wavelengths needs to be measured with an accuracy on the order of a few µm to yield mm- to sub-mm accuracy of refractivity compensated distances.

Mitigation of atmospheric effects is not the only potential benefit that motivates investigations of multiwavelength EDM. Gaining additional information with reflectorless measurements and in particular with laser scanning is another strong motivation. Apart from power bounds and angle-of-incidence effects [Gordon, 2008; Soudarissanane, 2016; Zámečníková & Neuner, 2017], reflectoreless EDM also suffers from uncertainties related to insufficient knowledge of the target properties. In particular signal reflection is affected by surface and sub-surface materials, surface structure and wavelength. The resulting systematic deviations may be larger than the associated random noise but practically applicable models for mitigation of these deviations do not yet exist [Zámečníková et al., 2014]. Broadband EDM combined with spatial scanning could enable recognition of the relevant target properties, e.g. surface material, by evaluating the spectrum of the returned signal and analyzing the path delay differences between the different wavelengths in addition to providing the raw distance measurement. Thus it can (i) lead to an approach for mitigation of surface and sub-surface effects on distance measurement, and (ii) allow remotely probing surface properties apart from geometry.

Some prototypes of hyperspectral laser scanners have already been proposed in the last years using supercontinuum pulsed lasers [Chen et al., 2010; Hakala et al., 2012; Powers & Davis, 2012]. These systems, however, are mainly focused on achieving enhanced detection and identification capabilities using the backscattered reflectance data. Spectrally-resolved distance information is also recovered from pulse time-of-flight measurements, but ranging accuracy is typically restricted to the cm level by the limited resolution of the direct delay observations. Achieving more accurate distance information would, apart from increasing significantly the identification potential in current applications, allow the investigation of novel techniques for material inspection based on short- to mid-range scanning.

The continuous advance in optoelectronics and, primarily, laser technology enables the exploration of alternative approaches to distance measurement. Mode-locked ultrashort pulse lasers are probably the most significant recent representative of this evolution. Since these sources, typically known as fs-lasers, became available around 15 years ago, their exceptional spectral and coherence properties have been exploited for numerous applications in time, frequency and distance metrology with outstanding results. The vast majority of distance-related applications using fs-lasers is based on complex interferometric set-ups aiming at highly accurate displacement measurements under laboratory conditions. There are, however, a few demonstrations of the feasible application of these sources to long-distance measurement in uncontrolled environments using the intermode beats generated by individual beams [Doloca et al., 2010; Jang et al., 2014; Minoshima et al., 2006; Minoshima & Matsumoto, 2000]. This method provides the required robustness demanded by longer propagation, sacrificing resolution, by making use of the spectral composition of the laser through self-beating to extract distance information without performing interferometry. Intermode beating represents a promising alternative to reduce the instrumental errors and increase the resolution of standard phase-of-arrival (PoA) implementations.

Spectral broadening techniques are increasingly available for this kind of lasers, which allows obtaining spectra covering several hundred nm from the visible to the near infrared regions. These broadband beams retain the fundamental properties of the original laser regarding spectral composition and phase coherence hence allowing, theoretically, the application of the same measurement principles. We are exploring the feasibility of using intermode beating with such broadened sources, aiming at establishing a flexible technological basis for future high-precision hyperspectral EDM. In this paper, we describe the fundamentals of the measuring principle and evaluate the feasibility of the method experimentally. A short-distance set-up is used to demonstrate that the internal noise and coherence of a broadened fs-laser are adequate to derive accurate distance information. We also identify dominant errors and limitations to be tackled during the further development.

2 MEASUREMENT PRINCIPLE

A mode-locked fs-laser emits trains of pulses of extremely short duration generated by the interference of a high number of modes with a fixed phase relationship in the laser cavity [Ye & Cundiff, 2005]. Due to this mechanism their optical spectrum, often referred to as frequency comb, is formed by thousands of equally-spaced narrow spectral lines typically within a bandwidth of some tens of nm. The spacing between the lines is defined by the pulse repetition rate f_r, which can be stabilized to a well-known value, e.g. a reference frequency from an atomic clock, by acting on the laser cavity length. When a fs-laser beam illuminates a square-law detector, such as a standard photodiode (PD), mixing between the comb lines occurs. This process is known as intermode beating [Seta & Ohishi, 1990]. It produces a frequency comb in the electrical output of the detector equivalent to the optical one. The output contains beat notes up to the detector bandwidth and equally separated by f_r. A representation of this relationship between optical and electrical spectra via intermode beating is shown in the power spectral density (PSD) plots in *Fig. 1*.

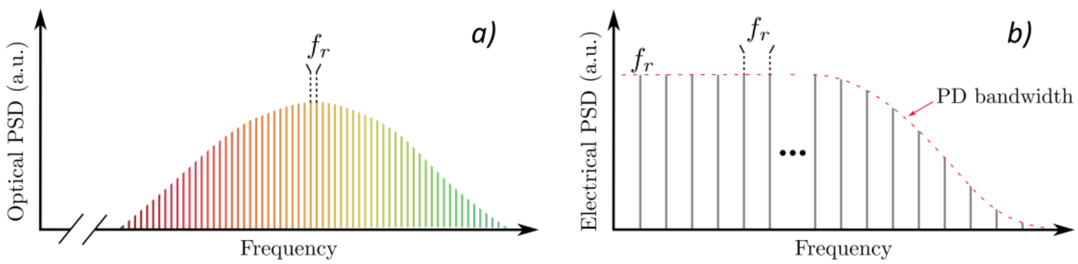

Fig. 1 a) Optical frequency comb generated by a fs-laser with pulse repetition rate f_r (line density reduced for clarity, idealized power profile). b) Corresponding electrical frequency comb generated via intermode beating in the output of a photodetector (PD).

Each of these beat notes contains information on the group delay of the optical signal, and can therefore be used to derive information of the propagation time by comparing it to an equivalent beam which covered a fixed reference distance. The phase of the q_{th} beat note is related to the propagated distance L according to

$$\phi(qf_r) = \frac{n_g(\lambda_c)}{c_0} 2\pi qf_r L + \phi_0(qf_r) \tag{1}$$

where qf_r is the beat note frequency, n_g is the integral refractive group index of air at the center wavelength λ_c, c_0 is the speed of light in vacuum, and ϕ_0 is an unknown phase origin. This phase offset is common to all beams from the same source and can therefore be cancelled by calculating the phase difference with the beat note of the same frequency detected in a different photodiode after beam propagation over a fixed reference path. In this case the estimated distance value is the difference between the distances over the measurement path and reference path, respectively. It can be calculated from the phase difference given sufficient knowledge of qf_r and n_g. This process is similar to the PoA measurements on sinusoidal intensity-modulated signals used by typical phase-based EDM systems. Through intermode beating, however, the modulation frequencies are obtained without the need of a modulator. This avoids cross-talking between measurement and driving signals, which contributes significantly to the error budget in standard implementations [Rüeger, 2012]. Additionally, a large number of modulation frequencies up to the detector bandwidth are readily and simultaneously obtained without any added complexity. This enables flexible configurations in which, for instance, resolution (as determined by the highest beat notes) and non-ambiguous ranges (dominated by the low frequency beat notes) can be adaptively chosen for optimum performance during data processing. Moreover, higher modulation frequencies yielding higher resolution can be obtained compared to intensity-modulated implementations, since they are now only limited by the detector speed and not by the typically smaller modulator bandwidth.

Using supercontinuum generation technology a fs-laser spectrum can be broadened from some tens of nm to several hundred nm while preserving, to a large extent, its original spectral and spatial coherence. A filtered portion of this broad spectrum can therefore be seen as equivalent to the original laser in a different band. It is consequently possible to apply it to measure distances using the intermode beating principle. These broadband beams could be used to probe distances with a truly hyperspectral source, where two or more spectral regions can be filtered right before photodetection to obtain distance measurements at multiple wavelengths of interest. The quality of the distance observations derived in this way will depend on how the broadening process degrades the properties of the original source. Experimentally demonstrating that these observations are sufficiently accurate for successful application to multiwavelength EDM based on intermode beating is the main goal of the present work.

3 EXPERIMENTAL SET-UP

The experimental demonstration of the proposed method is based on a 780 nm fs-laser (MenloSystems C-Fiber 780 SYNC100) broadened in a photonic crystal fiber (MenloSystems SCG1500). This equipment produces the spectrum shown in *Fig. 2*, corresponding to an integrated power of 100 mW over the spectral range from 550 nm to 1050 nm. For the experiment discussed herein, a small portion in the green region of this spectrum is filtered out to be used for the measurements. The spectrum of the filtered beam, centered at 570 nm and containing approximately 200 µW, is also shown in *Fig. 2*. The selection of this specific range was made considering both power stability and the adequacy of shorter wavelengths for prospective refractivity compensation experiments.

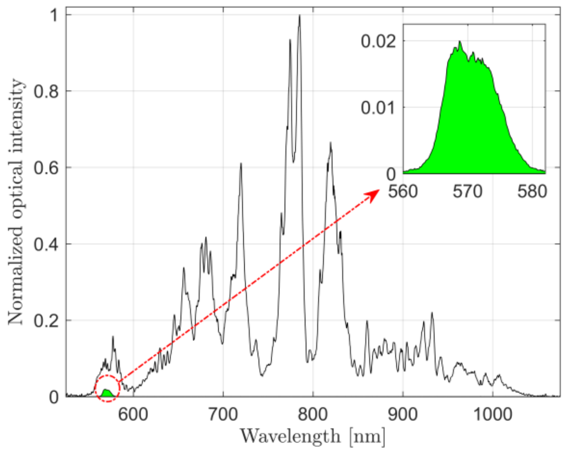

Fig. 2 Full supercontinuum spectrum of the applied laser setup, and filtered portion used for the measurements.

We have developed a short-distance set-up that uses this beam to probe the differential distance between a fixed and a variable optical path. The optical section of the set-up is shown schematically in *Fig. 3* and can also be recognized in *Fig. 4*. After filtering and conditioning the output of the supercontinuum laser, the beam is split into two paths. One of them is directly focused onto a detector for reference, while the other one propagates through a delay-line formed by a motorized translation stage and a broadband corner cube reflector before being focused onto the other detector. An alternative path can be introduced via flip-mirrors to bypass the delay-line and provide an internal reference path for the measurement detector. This path is used to compensate for low frequency variations of the overall delay of the measurement electronics, by performing a reference observation immediately before any actual measurement on the delay-line.

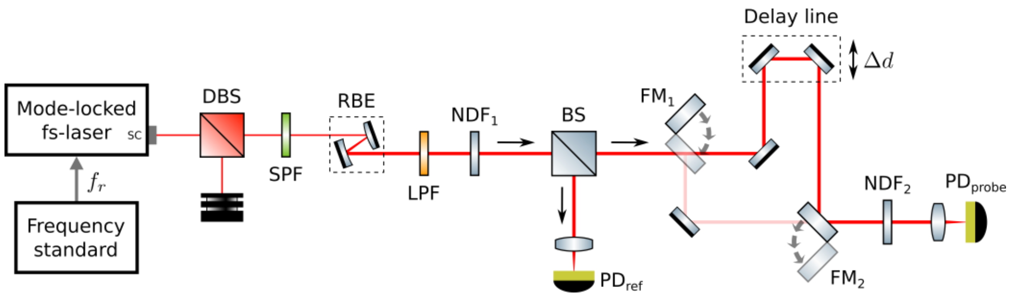

Fig. 3 Optical set-up for displacement measurements (DBS: dichroic beamsplitter, RBE: reflective beam-expander, SPF: short-pass filter, LPF: long-pass filter, NDF: neutral-density filter, BS: beamsplitter, FM: flip mirror, PD: photodiode)

The detectors are high-speed avalanche photodiodes that produce beat notes with sufficient quality up to 1 GHz. The differential distance information is obtained from comparing the phase of the 1 GHz beat notes of both detectors. To extract this phase difference, the output of the photodiodes is band-pass filtered and down-converted to shift the band of interest around 1 GHz to a lower band centered at 25 MHz for easier handling. The resulting signals are simultaneously digitized, and the phase difference between the down-converted digital signals is computed by synchronous In-Phase and Quadrature demodulation. To reduce uncertainty due to frequency errors, both the laser repetition rate and the mixing and sampling electronics share a highly accurate common time base derived from a rubidium frequency standard (SRS FS725). The laser head can be seen in the upper part of *Fig. 4*, together with the optical set-up for distance measurement.

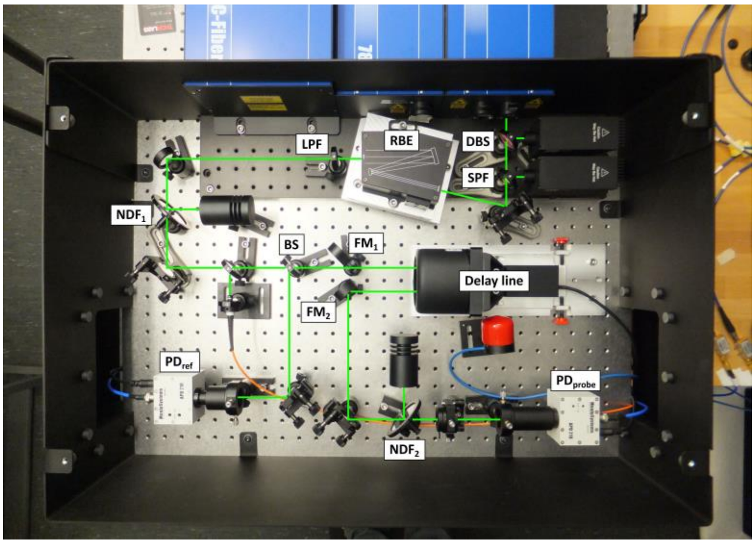

Fig. 4 Laser head (top) and optical set-up for displacement measurements.

4 RESULTS

Relative distances were measured varying the delay-line length in 5 mm steps up to 100 mm. While this may seem very short as compared to the potential applications mentioned in the introduction, it is easy to control and enough to demonstrate whether or not the intermode beating between comb lines obtained from a fs-laser supercontinuum can be used for distance measurement.

The measurements were calculated by integrating 40 MS acquired at 2.5 GS/s, corresponding to approximately 16 ms, which was a compromise between precision, amount of raw data and duration of the experiment. The distance values are referred to the initial position of the delay-line. The reference distance values are derived from the target positions of the delay-line, previously calibrated with an accuracy better than 15 µm by comparison with a Doppler interferometer (Agilent 5529a). The residuals between measurements and reference distances are shown in *Fig. 5a*, where each series corresponds to 1 out of 5 repetitions of the complete measurement process during 24 hours. Maximum and average errors are 110 µm and 30 µm respectively. As the figure shows, these errors are dominated by a clear cyclic pattern and a trend. The average standard deviation of the errors per position (i.e. excluding these two patterns) is just 11 µm, and even this value seems to still contain some systematic effects (the curves appear to be shifted vertically w.r.t. each other). So, the required accuracy for refractivity compensation of distances measured using cooperative targets seems to be feasible using intermode beating.

Further investigations are required to understand the dominant contributions to the systematics and to mitigate the associated errors. They can partly be associated with multiple reflection of the optical signals between components of the setup and similar effects introducing cyclic errors that could be mitigated by calibration. However, observations of the received power carried out simultaneously to the measurements point towards a relation of the errors with power and pointing variations (fluctuating as the corner cube moves). Amplitude-to-phase coupling and spatial non-linearity of the photodiodes have been previously identified as relevant sources of errors in related research [Doloca et al., 2010; Guillory et al., 2015; Minoshima et al., 2006]. This seems to be confirmed by our current observations, setting the stabilization or compensation of beam pointing and power fluctuations as a major challenge to be addressed for the practical application of this method.

To evaluate the precision and long-term stability of the system, static tests were also performed. The measurements showed high stability over periods of several tens of minutes. This can be seen in *Fig. 5b* where the distance deviation for a fixed length measured continuously over 60 minutes is shown. The individual estimations are again computed integrating 16 ms. The measurements exhibit a standard deviation of 18 µm; a significant improvement in precision is nevertheless expectable from accessing higher beat notes just by using faster photodetectors and adapting the signal conditioning electronics accordingly. Static measurements over longer periods of more than 60 hours showed drifts up to several hundred µm strongly correlated with long-term fluctuations of the laser power. These drifts induced a slowly varying distance offset which, due to the high stability in the shorter term, can be compensated with the reference measurements on the internal fixed path taken immediately before any actual observation.

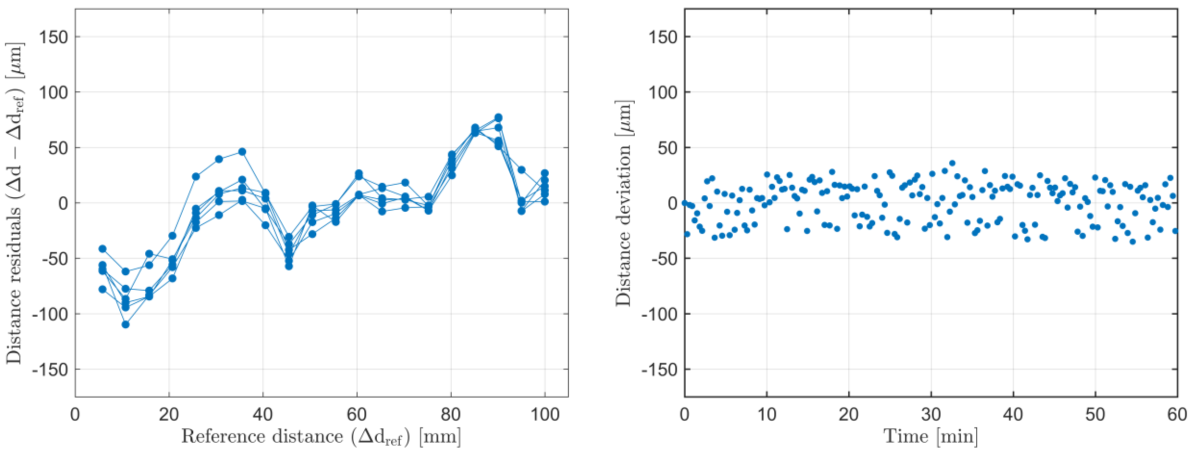

Fig. 5 a) Distance residuals between measurements and reference values as a function of delay-line length. b) Deviations of static measurement as a function of time.

5 CONCLUSIONS

We have briefly summarized the motivations for investigating multiwavelength or hyperspectral EDM and presented an experimental setup for EDM based on intermode beating of a phase-coherent broadband laser. We have succeeded in demonstrating experimentally the fundamental feasibility of using the intermode beats of a broadened fs-laser to measure distance. The achieved results show that the noise and coherency properties of a narrow portion of the supercontinuum spectrum are sufficient to derive distance information with a precision of some tens of µm. Pointing and fast power variations have been identified as relevant contributions to the error budget. These contributions may become serious challenges when transferring the method to (much) longer distances and to more realistic application scenarios (varying environmental conditions, turbulence, …). Therefore we will extended the experimental set-up to investigate these effects and their mitigation further when progressing to a dual-wavelength configuration over distances up to 50 m, before going into a geodetic baseline of several hundred meters.

The method presented herein has the potential to serve as a flexible technological basis for accurate multiwavelength EDM opening up opportunities both for increased accuracy through integral refractivity compensation and for remote surface material probing along with traditional laser scanning.

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