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Unmanned Aerial Vehicles in astronomy

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ABSTRACT

In this work we discuss some options for using Unmanned Aerial Vehicles (UAVs) for daylight alignment activities and maintenance of optical telescopes, relating them to a small numbers of parameters, and tracing which could be the schemes, requirements and benefits for employing them both at the stage of erection and maintenance. UAVs can easily reach the autocollimation points of optical components of the next class of Extremely Large Telescopes. They can be equipped with tools for the measurement of the cophasing, scattering, and reflectivity of segmented mirrors or environmental parameters like C_n^2 and C_T^2 to characterize the seeing during both the day and the night.

Keywords: Unmanned Aerial Vehicles, Drone, Telescope Alignment, Telescope Maintenance, Seeing

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), popularly known as drones, are used in a wide range of activities both for civilian and military purposes, for scientific and commercial scopes. Involved fields of interest are getting broader as technological developments make UAVs affordable and reliable tools to position sensors in locations otherwise difficult or unsafe to access or expensive for other options. The ability of UAVs to pinpoint positions with increasing precision and automation goes along with the evolution of laser ranging sensors in terms of compactness and lightness, allowing them to be employed in a number of metrological measurements for natural or artificial structures otherwise difficult to properly sense. UAVs have already been used in the inspection of powerlines,[1] bridges,[2] buildings,[3] mines,[4] as well as for 3D mapping,[5] in precision farming[6] or archaeology.[7]

Considering all these benefits, the use of UAVs in astronomy is a step to be considered for valuable contributions in making some procedures easier and cheaper. In the field of radio-astronomy, a hexacopter has been used to calibrate a single-dish radio telescope at the Bleien Observatory[8] and the Medicina Array Demonstrator.[9] Although applications of UAVs for strictly astrophysical objectives have not planned yet, we consider a wide spectrum of possibilities for them to be used as facilities for ground-based optical telescopes. Here we describe a non-exhaustive list of possible applications that we at least try to briefly discuss, emphasizing the applications in the field of alignment and maintenance of the telescopes and seeing measurements.

Nowadays, a dozen of 8 to 10 m diameter class telescopes are employed for astronomical purposes and the generation of Extremely Large Telescopes -ELTs- (diameter of 24 to 39 m) is in advanced phase of construction.[10–12] The alignment of these telescopes, in order to achieve nominal performances, is an important asset, especially taking into account the relatively high operation costs of such devices. Primary mirrors can be tested in daylight condition placing a calibration device in their center of curvature. Moreover, every time an intermediate real focus is identified, the optical train following such a point can be easily adjusted with a simple calibration device to be inserted in the proper position. Since for 30 m telescopes with a very fast ($F/1$) optical primary, such a device should be located at about 60 m away from the primary mirror to align it, and for popular Cassegrain telescopes the autocollimation point is even more distant to align the secondary, it is clear that the use of a UAV

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to reach those locations would overcome the need for expensive and inconvenient static structures, employed only in few cases.

Other examples of daylight activities of telescope maintenance, potentially performed by an adequately equipped UAV, are the measurement of the cophasing of adjacent surfaces, scattering and reflectivity of tiles of segmented mirrors. UAVs can be employed overnight in monitoring environmental parameters, like C_n^2 and C_T^2 that would be measured dynamically for an arbitrary thick ground-layer.

In this work we discuss the prospects of using UAVs for these mentioned activities: in Section 2 we consider two concepts to measure the environmental parameters and the seeing; in Section 3 we suggest how to use drones to align an optical telescope; in Section 4 other optical maintenance activities are discussed; Section 5 describes an experiment we performed in order to deal with the turbulence generated by the vehicle itself.

2. SEEING AND ENVIRONMENTAL PARAMETERS

Maybe the most easy-to-imagine drone application for optical telescopes is the *in situ* measurement of the environmental parameters that characterize an observing site during the site-testing campaign, the erection and maintenance of the telescope and the working time. The statistical analysis of temperature, pressure and humidity of the air and wind velocity and direction allows the characterization of the typical seeing of an astronomical site and provides crucial information for the calibration of adaptive optic systems, where this technology is or would be implemented, as in the case of the next generation of ELTs.

The use of UAVs to profile the wind pattern has already been considered mounting sensors on a fixed wing UAV[13] or monitoring its attitude during the flight:[14] this kind of measurements are useful to outline relatively large portions of the atmosphere around a location, but less typifying an astronomical site, since the goal is to obtain the values of the parameters as a function of the altitude or along the line of sight of the telescope. Usually the determination of these parameters is outlined by in-situ measurements, mounting the appropriate sensors on airborne balloons[15] or on static structures like towers or masts,[16,17] when the target to be monitored is the atmospheric ground-layer. In particular, towers and masts allow the determination of strong statistics and excellent repeatability of the tested positions; their limitation consists, besides the relatively high building cost, in the difficulty or impossibility to move the masts and the sensors on it, in the limited height and in the unique tested direction available.

Our simple idea consists in arrange a multi-rotor helicopter, equipped with the proper sensors, wherever one would demand the presence of a meteorological tower. In this manner one substitutes a static structure positioning the sensors arbitrarily in the space and keeping them -almost- fixed for an -almost- arbitrarily time, within the limits of the power supply. As we write, batteries are one of the main limitation of all commercial UAVs, since their lifetime usually does not exceed twenty minutes and becomes shorter adding payload to the vehicle. Luckily, it is rather simple to find commercial sensors with limited weight, but still high precision. Combining a differential thermometer and a pressure sensor one reaches the mass of a few grams and a volume of some square millimeters plus the weight of the microcontroller board and of the system to interface the sensors with the drone. With such a combination one can measure the value of the temperature structure parameter C_T^2 and relate it to the refractive index structure parameter C_n^2, which quantifies the magnitude of the atmospheric optical turbulence, through the relation:

$$C_n^2 = \left(\frac{kP}{T^2}\right)^2 C_T^2, \tag{1}$$

where P, T and k are the pressure, the temperature and a constant respectively.

Besides the *in situ* evaluations, the other way to monitor the atmospheric turbulence around an astronomical site is using remote sensing techniques, like SCIDAR,[18–20] Single Star Scidar,[21] SLODAR,[22] MASS[23,24] or DIMM.[25] These methods are based on the observation of single or double stars that provide scintillation or slope profiles that can be correlated to the turbulence of an atmospheric layers. Where the telescope is equipped with laser star technology, real stars can be replaced by artificial stars,[26] using the same ground instrumentation and taking into account some differences due to the finite distance of such luminous sources.

Taking into account the specifications of various techniques and the limitation in sensitivity and resolution for a given source height, one can use an UAV as carrier for luminous sources, by mounting one or two laser:

this is the most straightforward way to have a single or a double source of light. This solution can be lightened further replacing the lasers with retroreflectors to be illuminated from ground, or reflecting spheres that would produce a point-like image of the sun.

The configuration of the UAV we propose for the turbulence analysis consists in mounting the devices on a horizontal bar fastened under the vehicle. For *in situ* measurements this setup provides the separation between thermometers to calculate differential temperature. For the light sources it is a way to control their angular separation (for double sources) for an arbitrary height (*i.e.* for an arbitrary thickness of the ground-layer). This bar must be long enough to avoid the influence of the air turbulence generated by the drone propellers (Section 5) and can be connected to a gimbal mount to enhance stability and to an Inertial Measurement Unit in order to record the differential motion of the sources in the space.

All the proposed devices can be employed both during the nighttime activities of the telescope and during daytime, in order to increase the statistics of measured parameters of the ground-layer and to validate the results taken with already available facilities.

3. TELESCOPE ALIGNMENT

The performances of an optical telescope are obviously enhanced with better alignment and calibration. For an optical system, every time an intermediate focus is foreseen, it is possible to perform an alignment of the following train of optics, just putting the right device in or around that focus. For instance, one smart configuration is the Gregorian design of the Large Binocular Telescope[27] which allows, with its finite focus between the primary and the secondary mirror, for necessary inspection and calibration of the adaptive secondary mirror in daylight time. Daylight monitoring of other optical configurations, *i.e.* common Cassegrain or Ritchey Chrétien telescopes, is more difficult, since they usually do not take into account for real finite intermediate foci between the principal mirrors.

Another option to inspect the primary mirror of a telescope consists in putting a source and a sensor in or around its autocollimation point, *i.e.* the center of curvature of its osculating sphere. This method is implemented for daylight autocollimation at the Hobby-Eberly Telescope at McDonald Observatory[28–30] and at the Southern African Large Telescope,[31] where towers were built in the vicinity of the dome in order to position a calibration unit (Center of Curvature Calibration Sensor) around the center of curvature of the primaries to align the 91 hexagonal segmentes which make up the mirrors (Figure 1). A similar solution, besides having the obvious disadvantage to represent a permanent obstacle in the field of view, would be much more onerous with respect to the provided benefits if applied to the next generation of ELTs. Just to have an idea of the order of magnitude for the location of the autocollimation points, let us consider a relatively small telescope, *i.e.* the Italian Copernico Telescope in Asiago, a Cassegrain with a 182 cm entrance pupil. The center of curvature of its primary is at about 11 m from the vertex of the mirror, well outside the dome. This distance scales with the dimension of the telescope, given the focal number: for an eight meters class telescope, this value is about 30 m and for an ELT, characterized by a diameter of $24 - 39$ m, one reaches $60 - 70$ m, depending on the focal number of the mirror.

Furthermore, besides the obvious autocollimation solution for the primary mirror, we consider which are the involved distances for the monitoring of the secondary one. In 32 we consider a simplified Cassegrain telescope characterized by only three parameters (diameter, primary focal number and magnification factor): this can be done if the focus of such a telescope coincides with the vertex of the primary mirror and the dimension of the secondary is neither over nor under sized considering null field of view. From this configuration, we extracted simple formulas to relate these three parameters to the approximate positions of the autocollimation points P_1, for the primary, and P_2, for the inspection of the secondary through the primary (Figure 2). These formulas can be applied to actual configurations since they fit the results of ray-tracing simulations of actual telescopes. P_2 is the point from which a light beam shot toward the center of curvature of the secondary mirror, through the primary, comes back in P_2 itself. For an eight meters class telescope, the distance of P_2 from the vertex of the primary mirror is about 100 m and for an ELT is about $250 - 300$ m, depending on the telescope. Therefore the choice of a tower to arrange a calibration unit would be an even more inopportune option.

As for environmental measurements, we suggest to replace (or add beside to) big fixed structures with an UAV hovering around P_1 or P_2. The UAV would carry the calibration devices, in this case a laser to illuminate

Figure 1. Towers are employed to house the Center of Curvature Calibration Sensors, to align the mirrors of the Hobby-Eberly Telescope (left) and of the Southern African Large Telescope (right).

the mirrors, and a sensor to measure the back-reflected light, which would be a point in the ideal configuration without optical aberration, or a pattern with dimensions and features which are distinctive of various telescopes and aberrations to be corrected, in the actual cases (Figure 3). In 32 we will show that the fractions of sensed mirrors enlightened from the autocollimation points are between 90% and 98% and the difference between these areas and the ones illuminated by a source at infinity is a few percent.

Another analysis we will provide in 32 is the characterization of the dimensions of the backreflected pattern which would be measured by sensors flying with the drone: while for a small telescope (*i.e.* Copernico) this patter has a typical diameter of some millimeters, for an ELT the size increases up to about 900 mm. This feature affects the instrumentation to use and its implementation on the UAV. We propose to mount a screen under the UAV that must be wide enough to intercept the whole back-reflected pattern; a laser inserted at the center of the screen can shoot the beam of light toward the telescope and finally a camera is positioned looking toward the screen so that it can take images of the back-reflected pattern to be analyzed. In Figure 4 we show a simplified depiction of the concept described and a possible implementation of the instrumentation.

As we already pointed out, one of the advantages of the UAV is the possibility to provide a daytime tool in order to increase, or use more efficiently, the time dedicated to the maintenance of the telescope. However, in this case, and whenever the aperture of the dome is necessary, one should consider also other parameters in order to avoid errors and conflicts. In particular, in preparation for an observing night, the temperature within the dome is preset in advance to fit the predicted external air temperature, in order to avoid air convection and thermal stresses on both the mirrors and the frames which would result in a seeing degradation. Therefore, a

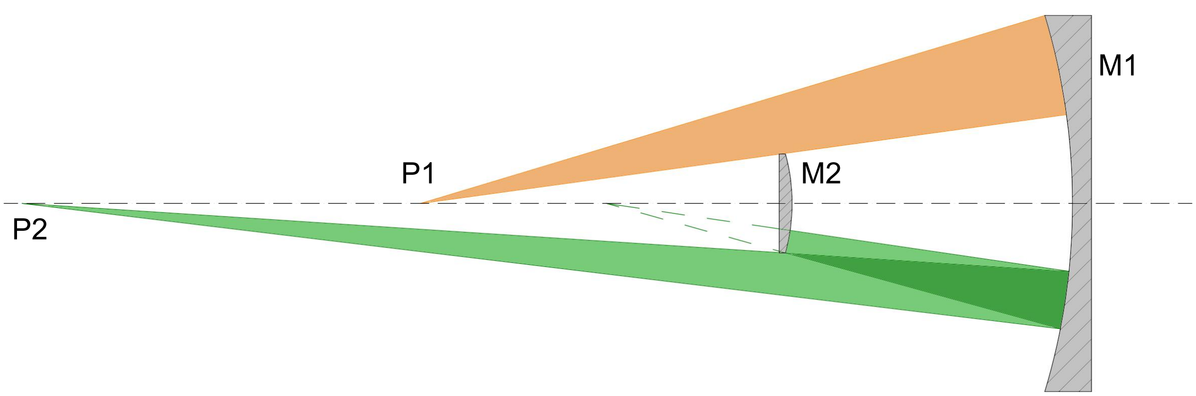

Figure 2. P_1 and P_2 are the autocollimation points for M1 (the primary mirror) and for M2 through M1 respectively: P_1 coincides with the center of curvature of M1, while P_2 is the conjugate of the center of curvature of M2 through M1.

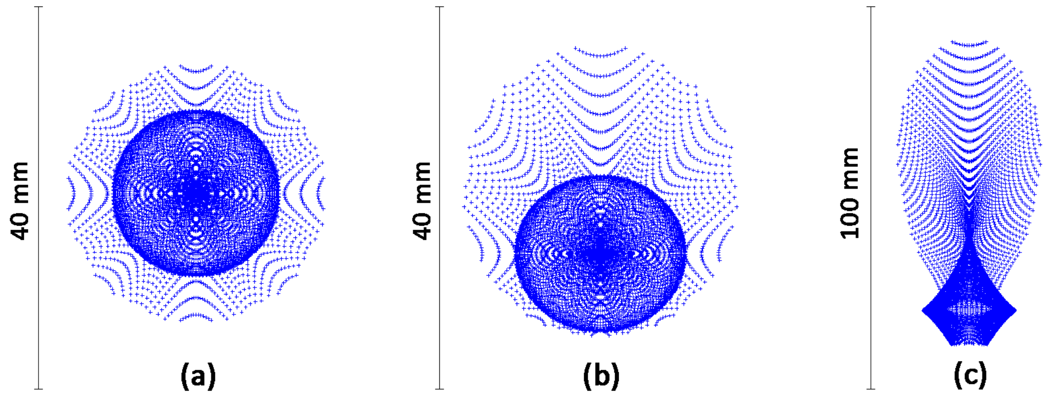

Figure 3. A simulated example of a backreflected ray-tracing diagrams seen from the autocollimation point of the secondary mirror (through the primary) of a 8 m class telescope (in particular we used the Very Large Telescope parameters to produce this picture). (a) is the pattern when the telescope is perfectly aligned; in (b) and (c) we simulate an exaggerated tilt of the secondary of 0.5° and 2° respectively.

suitable moment would be at sunset, at the dome aperture, or at dawn, after the scientific use.

4. OTHER OPTICAL APPLICATIONS

4.1 Cophasing

The largest monolithic mirrors in use are currently the two primary mirrors of the Large Binocular Telescope, each one with a diameter of 8.4 m; for larger diameters the technology of segmented mirrors is applied in order to avoid the prohibitively costs of both an equivalent monolithic mirror and the massive structure needed to transport and support it.[33] Segments overcome these problems since their manufacture, transport and upkeep are much easier. The drawback of this technology is that each segment requires to be phased to the other tiles, since the image quality is strongly affected by wavefront errors introduced by the segment aberrations including segment misalignment; also the Strehl ratio decreases rapidly with an increase of the phasing error.[34] The segments alignment should be constantly monitored with active control sensors, since it is affected by wind,

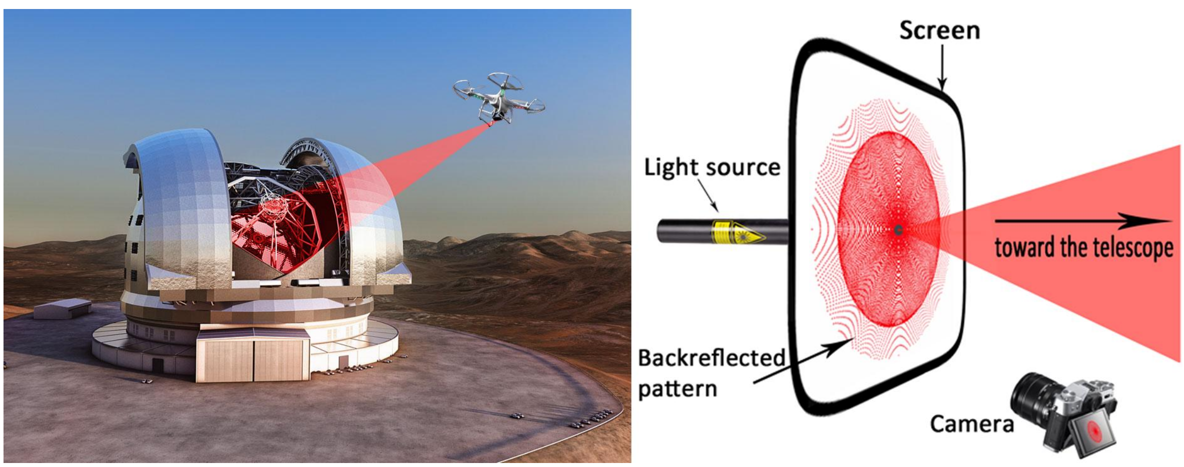

Figure 4. Left: the concept described in the text, where a drone is used to optically sense a telescope mirror; right: since the backreflected pattern of a laser beam through large mirrors exceeds the dimension of typical commercial CCDs, the proposed solution is to take pictures of a screen which intercepts such pattern.

vibrations of the structures and thermal variations. Furthermore, the measurement of cophasing is essential every time a new segment is installed or replaced for re-coating. There are several optical phasing techniques[35–44] to be implemented periodically to calibrate a segmented mirror and they are carried out both before observation by pointing bright sources, and during scientific observations, provided a sufficient bright source in the field of view.

The use of an UAV would extend the time available for the calibration including also the daytime to the suitable moments for this operation. One option is to exploit the configuration described for the autocollimation of the telescope (Section 3) and adapt it in order to monitor small portions of mirror, *i.e.* composed of a few segments, at a time. In this way one would position the copter in the autocollimation point of such a "submirror", illuminating it with a laser and collecting the backreflected pattern in order to analyze its shape correlating it to the misalignment features of the segments. Then one would point the drone toward another area to enlighten another portion of the mirror, partially overlapped with the previous one, in order to generate a "stitching calibration" as depicted in Figure 5.

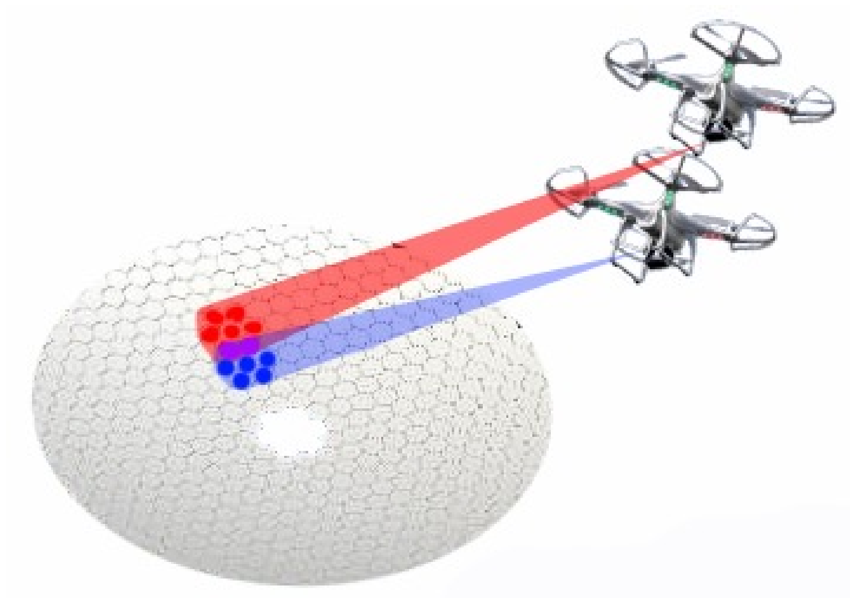

Figure 5. A pictorial example of the use of an UAV applied in a cophasing procedure. The drone illuminates a few tiles of the mirror from their autocollimation point and analyze the backreflected pattern; then the vehicle moves on another location to align other segments partially overlapped to the previous one, and so on covering the entire mirror.

The principle of curvature sensor can be exploited in such a test: the drone can record the intensity of the intra and extra focal image and if the incoming wavefront is free of aberration, the two planes are uniformly illuminated. Otherwise a local curvature variation would produce an intensity difference correlated to wavefront aberration.

4.2 Reflectivity and scattering

The capability of some UAVs to carry a relative heavy (some kilograms) load, allows for the employment in the inspection of single mirror tiles or portions of a monolithic mirror in terms of reflectivity and scattering. One can mount a calibrated source to illuminate the mirrors and a gloss meter or an integrating sphere to measure the intensity of the reflected light. To measure the reflectivity or the scattering at wide angles one can think to position the source inside the dome or to use a couple of drones to split the instrumentation.

5. OPTICAL EFFECT OF PROPELLER-INDUCED TURBULENCE

Among all other intrinsic drone characteristics which can represent a limitation for our purpose, we first consider the turbulence induced by the drone itself that can pollute the measurements of air turbulence or distort the luminous signal during the other experiments.

A physiological and intrinsic problem to deal with is the fact that a multi-copter must move air in order to fly. This feature can be qualitatively noticed also on very small drones, simply putting a hand under the vehicle itself. Since this behavior would affect the design of the UAV, we set up an experiment in order to measure it. In particular, we want to understand which is the volume, under the propellers, where the induced air turbulence affects the wavefront of a laser in order to position all the needed sensors outside that area *e.g.* mounting them on a long enough carbon fiber (or another light and strong material) bar. We mounted a small (3 μW) Thorlabs diode laser (635 nm) with a 5X beam expander at about 1.5 m from ground and shot a horizontal light beam toward an Edmund Optics CCD (1280X1024(5.2 μm)px) positioned 25 m away, and we recorded a rapid series of 128 images in order to establish the "background turbulence". Then we drove a DJI Phantom3 letting it hover in 12 points on a grid over and next to the laser beam: we put 4 control target on the ground, the first on the laser path direction, the other on a perpendicular direction, one meter away each other. The drone can position itself over the targets using its built in camera. The three positions (2, 3 and 4 meters) over each target where reached following the altitude output of the drone software. For each position we acquired a rapid series of 128 images. The whole experiment was also performed putting a screen 70 m away from the diode and recording the produced spot (larger than our CCD, at that distance) with a Nikon D7000 + 200 mm lens positioned in front of the screen. A scheme of the setup is shown in Figure 6.

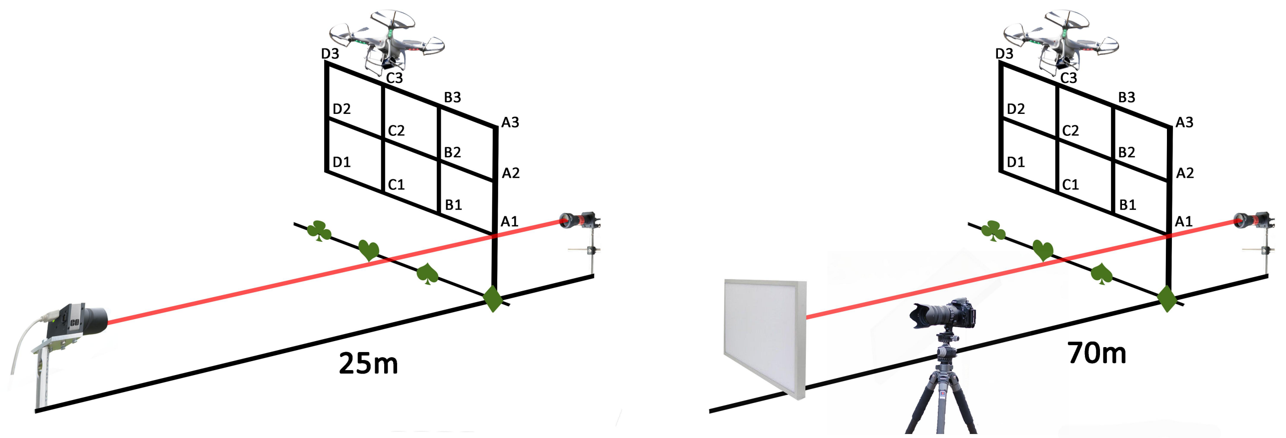

Figure 6. A scheme of the experiment setup. The card suits represent different objects positioned on the ground perpendicular to the laser beam and separated by 1m: the drone flies over them thanks to its own camera looking toward the ground. The vertical position is controlled by the drone software. Laser and CCD are 25 m far away in the left panel configuration; laser and screen are 70 m far away in the right panel configuration. The distance of the camera from the screen is 2 m.

Unfortunately the results of the experiment are a bit noisy and cannot be used to accurately describe how the volume under the drone is affected by its own turbulence, since we recorded a clearly perturbed set of images just in the position B2 (see Figure 6) with the 70 m setup, as reported in Figure 7: here we plot the distance in arcsec of the centroid of each taken image in the B2 run and the average distance (dotted line), showing how the propellers-induced turbulence increases the mean scatter angle $\bar{\alpha}$ by about 1 arcsec. This was related to the unstable flight of the quadricopter used in a relatively windy day and to the relatively low sensitivity of the method due to short distances between the laser and CCD. So this experiment should be considered as a preliminary trial and a lesson learned for the setup and conditions to be employed in order to have accurate measurements.

6. CONCLUSIONS

Some options of the employment of an UAV as a tool for the inspection, calibration and maintenance of the mirrors of optical telescopes and for the measurement of environmental parameters in the vicinity of telescope

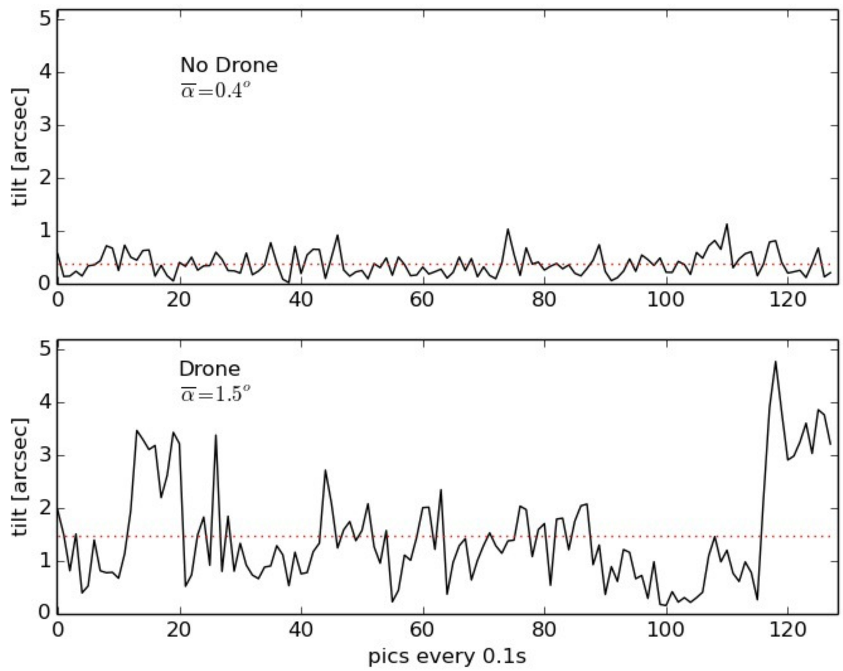

Figure 7. The scattering of the centroid position of a rapid series of images of the spot for an unperturbed setup (upper panel) and with the drone flying over the laser beam (lower panel).

domes are presented. We discussed how the drones can be an easy solution as carrier of small and lightweight, but precise sensors for temperature or pressure measurements and for optical instrumentation like laser sources or retroreflectors. We highlighted that multi-copters are an inexpensive alternative to meteorological and "center of curvature" towers, due to their relative ease in control and for their capability, stability and traceability during the hovering. We described the setup for an experiment to analyze the air turbulence generated by the drone itself in order to avoid a possible UAV setup where the measure to be done would be intrinsically polluted by the rotation of the propellers.

The solutions proposed throughout the article can highlight unforeseen and non trivial problems during their implementation. Every final and workable UAV configuration, *i.e.* the type and weight of drone load, the trajectories of the flights and the locations of the hovering, the time of the operations and so on, must undergo the regulations provided by the Civil Aviation Authority of a given state, which often forbids the flight in some critical conditions, such as the vicinity to airports, or beyond typical distances to the pilot or to the ground, or during nighttime. Furthermore, although the proliferation of the UAV in several research and commercial field has prompted Aviation Authorities to regulate them, the relative newness of the phenomenon implies frequent changes and improvements and difficulties when try to match laws of different states. Since the safety of people and valuable instrumentation is involved during an UAV operation, we recommend to pay attention to such regulations which often imply criminal convictions (an example of UAV regulation for the Italian case can be found here 45 and here 46).

From a technical point of view, besides the short battery lifetime (already cited in Section 2), a limitation for the use of UAVs in visible astronomy comes from the difficulties to keep them stable during the hovering within a few centimeters threshold and to track the position of the sensors even more precisely. The efforts in this direction are promising and take into account both direct positioning, through differential GPS,[47] and vision techniques.[48–54]

Considering the progress in both UAVs and optical instrumentation, the capability to complete complex missions without an on-board pilot, increasing the possibility to reach uncomfortable and unsafe places, we believe that UAVs would provide an additional and convenient tool to be exploited in the field of optical astronomy.

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