4DAD, a device to align angularly and laterally a high power laser using a conventional sighting telescope as metrology

Christophe DUPUY, Thomas PFROMMER, Domenico BONACCINI CALIA
European Southern Observatory, Karl-Schwarzshild-Str.2, 85748 Garching bei Muenchen, Germany

ABSTRACT

The 4DAD, Four Dimensions Alignment Device was developed in the frame of the project 4LGSF (4 Laser Guide Star Facility) for the AOF[1] (Adaptive Optics Facility) on the ESO VLT (Very Large Telescope). It is used to accurately align with respect to kinematic interfaces and mirror alignment targets, a 20 W-class laser source in lateral and angular directions. 4DAD is of size 25x25x15cm and is based on a commercial CCD beam profiler.
The incoming beam is highly attenuated at 589 nm and split in two parts through a set of beam conditioning optics. One beam is directed onto the detector revealing lateral movements whereas the other part is refocused to reflect angular changes in the incoming beam. Both lateral and angular beam positions are simultaneously recorded as pixel coordinates on the single CCD.
The distinctive feature of 4DAD is its metrology, i.e. the pixel reference coordinates are recorded through the cross projection from a conventional sighting telescope. The device is capable of being used with a low-power white light sighting telescope (alignment reference) as well as with a high power laser beam (to be aligned) without any optical configuration change.
Mounted on a reference frame, it can align all 4LGSF laser units beams, giving them equal optical interface and interchangeability.
The sighting telescope is the main alignment equipment for the 4LGSF, thus all sub-systems, including 4DAD are aligned, merged, using a simple, single, practical and well-known alignment instrument.
The alignment strategy, the design, and results of 4DAD are presented.

Keywords: 4DAD, 4LGSF, AOF, alignment, kinematic, sighting telescope, high power laser, CCD beam profiler

1. INTRODUCTION

The 4LGSF uses 4 laser guide star units (LGSU), each composed of a laser head[2], a Beam Conditioning and Diagnostic System (BCDS), an Optical Tube Assembly[3] (OTA launch telescope). One of its requirements is the interchangeability of the laser head on an existing BCDS structure without having to realign the laser head optics or beam conditioning optics. It is thus required to pre-align the laser head onto pre-set and stable target coordinates in lateral as well as in angular directions.

4DAD is used to accurately align with respect to kinematic interfaces and mirror alignment targets, all 20 W-class laser beam in lateral and angular directions. Its size is 25x25x15cm and hosts a commercial CCD beam profiler. The incoming high power laser beam passes through a highly reflective mirror (HR at 589 nm) and dumps most of its energy in a beam dump. The leaking photons are subsequently split into two parts by using an additional highly reflective mirror (at 589 nm). The passing beam, now sufficiently attenuated, goes straight onto the CCD detector, revealing lateral displacements (x,y). The reflected beam off the second HR mirror still contains too much energy to be directly imaged onto the CCD. After passing a 500mm EFL focus lens, it is folded, using two bandpass filters (BP) and two mirrors. The BP filters reflect only a small fraction of the 589 nm photons and two in a row attenuate the focused beam well enough to not damage the CCD. This second beam is directed onto a different area of the CCD detector, revealing angular displacements (θ, φ). Both beams are Gaussian and their shape can be visualized on the detector. Both lateral and angular beam centroids are simultaneously recorded as pixel coordinates on the single CCD.

4DAD not only allows visualizing high-power laser light, tuned to 589 nm, but also can be used with a conventional alignment telescope. This is used as metrology tool to identify the pixel reference coordinates in both lateral and angular direction for pre-calibration purposes through the projection of a target (dark line reticule on bright field).

The low-power white light reference sighting telescope (ST) is used on 4DAD in the exact same configuration as with the high power laser beam. No optical configuration change is needed, which increases the reliability of the results, especially if used under high precision alignment specifications. Mounted inside a dedicated reference BCDS frame, it is used to align all laser units output beams, giving them equal output beam positions and allowing the required laser head interchangeability. It will be used to verify/adjust the laser pointing after transport to Paranal (Chile) and in addition it will be used for environmental load tests of the laser beam pointing.

The ST is the main alignment equipment for the 4LGSF, thus all sub-systems, including 4DAD are aligned, merged, using a simple, single, practical and well-known alignment instrument. The alignment strategy, the design, and results of 4DAD are presented. This work is done by the ESO 4LGSF team.

2. 4LGSF ALIGNMENT STRATEGY

The 4LGSF alignment strategy is to have each optical subsystem input/output optical axis independently referenced with respect to each other. This will in the end allow the interchangeability of the single subsystems. The final system alignment process ends with a merging of all subsystem optical axes on a single line of sight.

This approach is mainly selected due to the fact that one subsystem is defined as a line replaceable unit (LRU), i.e. interchangeable. It is as well particularly suitable when more than one subsystem has to be built and aligned either by different teams or at different premises, thus allowing tasks to be independently parallelized. Interfaces shape and position for each subsystem have then to be carefully addressed at the early design phase and must respect basic kinematics laws.

This strategy perfectly fits with two subsystems of the 4 LGSF. The first one is the laser head, defined as a LRU, built and aligned by the company TOPTICA. The second is the BCDS built and aligned by ESO.

As shown in Figure 1, each LGSU (~800kg) consists of a base plate (1), an OTA (2), a BCDS (3), and a laser head (4).

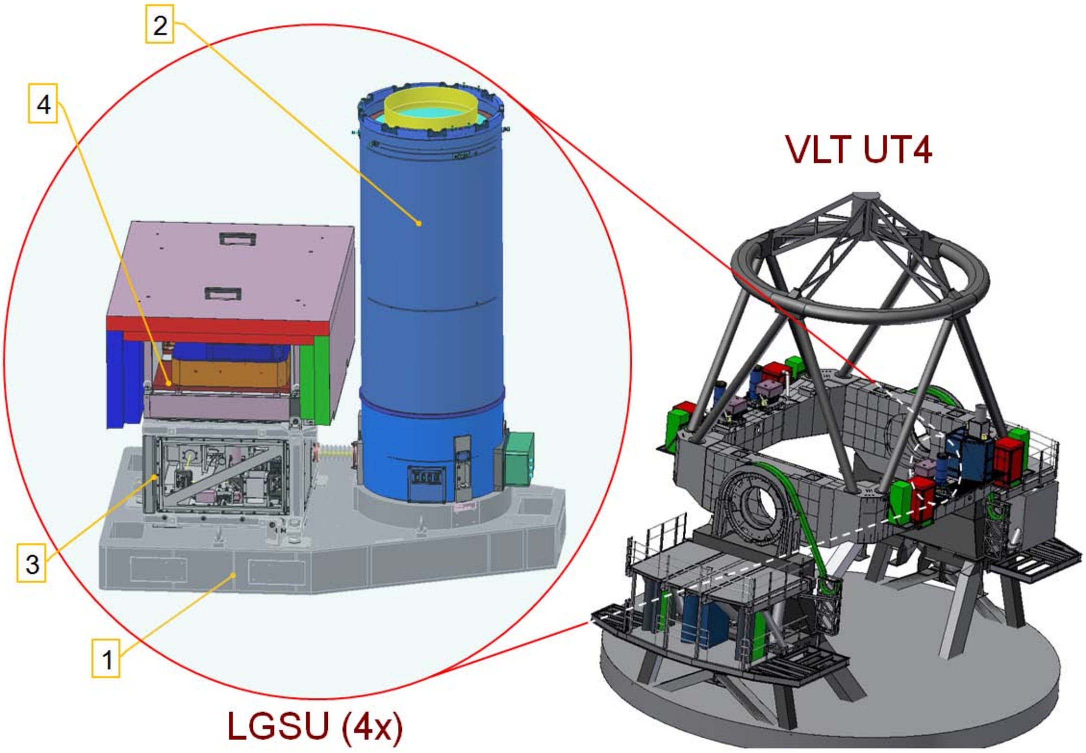

Figure 1: LGSU subsystems

The OTA optical axis is defined by its input interface. The BCDS is internally aligned with respect to input and output interfaces. The BCDS frame is adjusted on the base plate and its output axis is merged to the OTA input axis. Mechanical interfaces are “transferred” into optical axis and vice versa through a set of reference targets described in chapter 3. All these steps are carried out using traditional optical alignment means like a bright line alignment telescope. Note that such sighting telescopes are commonly used and available on remote observation site.

This simplified sequence can unfortunately not directly be applied to the laser head onto the BCDS as one has to sight the 4.2mm 20W laser beam (589nm) to get it aligned with the BCDS input opto-mechanical interface. To overcome this issue, we decided to use an intermediate module allowing us to transfer the reference line of sight (centration and angular deviations) obtained with the alignment telescope into coordinates to be later on, used for aligning the laser used in operational conditions.

An investigation for available commercial modules was unfortunately not successful and therefore obliged us to develop and build our own system, the 4DAD.

3. ALIGNMENT REFERENCE TARGETS

Input and/or output optical axes of subsystems are defined by a set of custom made reference targets. These reference targets as shown in Figure 2, are built at ESO from flat parallel mirrors equipped with an opened target. The target, machined with laser cutting means, is directly glued onto the reflective surface and is concentric within a few microns either to the outer mirror edge or to an additionally mounted alignment ring (see Figure 2). Target and mirror shapes, sizes are defined according to the later subsystem interface and alignment requirements.

The mirror edge is usually in contact with a V-shaped interface, so that the target defines the interface center optically, meaning the center is the point which belongs to the optical axis. The flat parallel mirror is usually seated on three balls or small surfaces, spaced at 120°, so that the normal to the mirror defines the angular direction. Point (sighting) and angular direction (autocollimation) both define a single virtual line in space linked to mechanical interfaces.

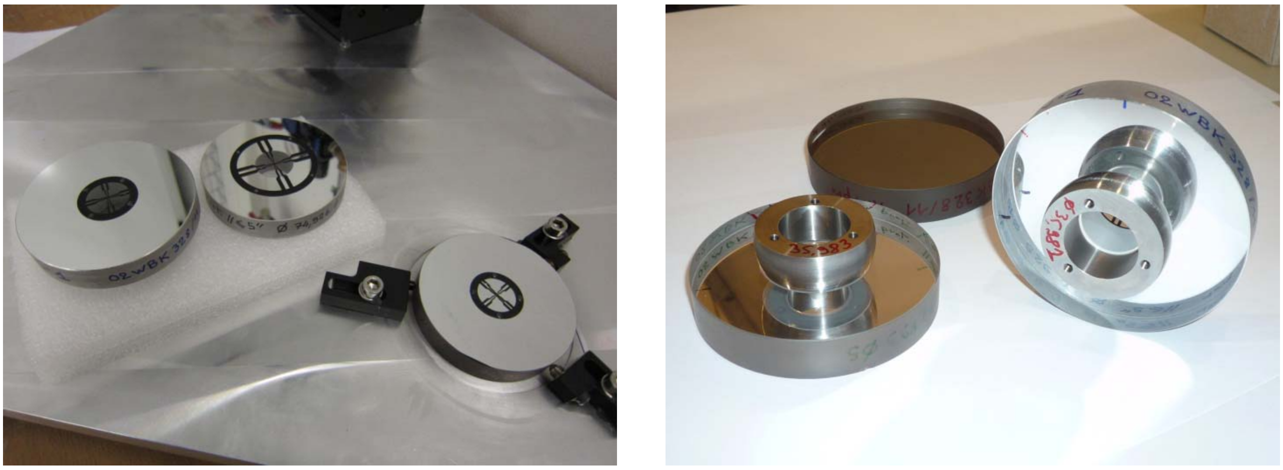

Figure 2: Alignment reference targets

4. BCDS AND LASER HEAD REFERENCES

4.1 BCDS dummy

To comply with the alignment strategy, 4DAD is a device which is mounted inside a reference BCDS frame dedicated to the internal alignment of the laser head. This frame, called BCDS dummy provides a unique opto-mechanical reference onto which the four laser heads of 4LGSF have to be aligned in Europe, and can be checked after transport to Paranal, as well as for maintenance purpose.

The BCDS dummy is composed of identical parts (frame, covers, and internal breadboard) like the final BCDS. All other internal BCDS components are replaced by the 4DAD sensor, which is directly clamped to the breadboard. This is shown in Figure 3.

Figure 3: 4DAD inside BCDS

Each laser head is attached on top of the BCDS dummy, interfaced on three small surfaces and pushed against three lateral stops. Cancelling all 6DoF, we ensure this way an optimal laser head positioning repeatability and as well a unique beam centration and angular position with respect to the BCDS frame.

4.2 Laser head dummy

The laser head dummy is a tool kept at ESO Garching, which provides a common reference optical axis and mimics the laser head frame interfaces. This axis is defined by a reference target which is positioned nominally on a 3D measuring machine. Combined with the sighting telescope, the laser head is used to:

- Define the 4DAD reference pixels laterally and angularly with low power white light. Those coordinates are used to align each laser head with high power on the 4DAD
- Define the optical axis for positioning all BCDS internal subsystems

5. 4DAD FEATURE REQUIREMENTS

The table below provides the 4DAD main requirements, which were used to identify a potential commercial product or for the chosen in-house design. The two last columns provide comments related to our investigation and final choice.

Specifications					
Function	Range	Resolution	Absolute accuracy	Off the shelf product	4DAD
Lateral beam position	>5mm	<2.5µm	<5µm	Many items compliant with different technology like PSD or CCD	Duma BeamOn HR based on CCD with pixel size of 4.65x4.65µm
Angular beam position	>30 arcmin	<2.5arcsec	<5arcsec		Duma BeamOn HR coupled with a 500mm fl lens

Features		
	Off the shelf product	4DAD
Interface onto BCDS breadboard	With additional adapters	By design
Simultaneous recording of lateral and angular beam position	Available, based on PSD, i.e not compatible with dark cross recording	Fulfill
Able to record position of low power dark cross with white background and high power 589 nm laser	None	Fulfill
Automatic laser centroid recording	Many available	Fulfill
Beam profilometer capabilities	Many available	Fulfill
Turn key recording software	Linked to the device selected with different level of features among product	Fulfill
Cost effective	Factor 1 to 3	Less cheap solution considering development and design

As seen in the table, the main parameter, which pushed us towards an internal development, was clearly the feature of recording the position of a low power dark cross and as well a high power 589 nm laser beam. The CCD as detector appeared to be the optimal solution in terms of absolute position recording, beam or cross visual inspection, as well as related software features.

6. 4DAD DESIGN

6.1 Breadboarding

The design started by selecting the recording device. The fact that suitable components, like the high reflective HR mirror at 589nm or the beam profiler from Duma, were already available in-house has influenced our design choices and strategy. We had some experience with this CCD and could right away proceed with tests such as dark cross visual inspection and laser beam-fringing effect. In the early design phase, we proceeded first with a breadboarding approach where we could validate all parameters using low power laser beams.

6.2 Optical design

Incoming photons enter 4DAD from the top and are folded horizontally via a 45° folding mirror.
M1 reflects the high power 589 nm laser beam by up to 99.9% onto a water-cooled internal cone absorbing beam dump while allowing most of the visible spectrum to pass by. The second HR mirror (BS) splits the beam into the angular and lateral diagnostic part. On the angular path a 500 mm focus lens images the beam onto the CCD. Before, however the beam is folded via M2 to M5 where M2 and M3 are the already address BP filters and M4 and M5 are aluminum coated conventional flat mirrors. This setup allows for high resolution due to the large focal length but in the same time makes a compact housing. The BP filters are best used at 10° angle of incidence and only reflect 0.7 % at 589 nm, while reflect most of the other visible light.
Both beams are in the end projected onto the sensor active area of 7.6 x6.2 mm. The lateral beam does not pass any powered optical surface and represents therefore the natural collimated laser beam at that location. The white light from the ST is used in imaging mode and thus a sharp cross is imaged onto the CCD for the lateral position. The angular beam path focuses the laser beam onto a small (30 micron) wide spot and the ST white light beam in autocollimation mode is imaged by the same path, producing a dark cross on the detector.

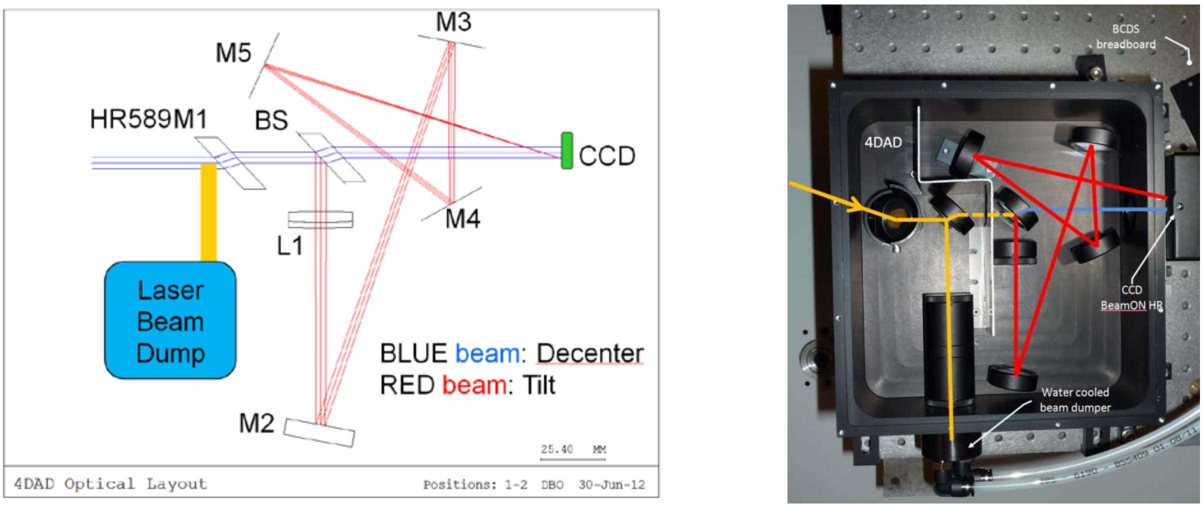

Figure 4: 4DAD optical layout

4DAD coatings		
Components name	Coating	T or R (measured)
Entrance folding mirror, M4, M5	Protected aluminum	R>90%
M1, BS	High reflectivity for 589nm at I=45°	R>99.97% T<0.03%
M2, M3	Bandpass filters for 589nm at I=10°	T>99.3% R<0.7%
L1 achromatic doublet 500mm Fl.	400-700 antireflection	R<0.5%
CCD sensor	None as front protective glass removed	

The flux of the 20W high power laser beam onto the CCD is:

- Lateral beam ~ 2.2 µW
- Focused beam ~ 0.03 µW

Considering that the focused beam is confined within a few pixels, these values are fully compatible with the sensitivity and saturation of the chip.

6.3 Mechanical design

As shown in Figure 3, a rather compact design and a housing of 25x25x15 cm were chosen.
The housing is machined from a cast aluminum block and is clamped onto the breadboard by three feet. A top cover can accommodate a small cap (against dust pollution) or an iris diaphragm.
All optics of 25mm diameter are integrated and glued inside standard compact mounts. After internal alignment, mounts are attached to the housing with M4 screws and are secured with a joint of epoxy glue.

7. 4DAD REFERENCING AND RESULTS

7.1 4DAD referencing

4DAD reference coordinates are directly linked to the laser head dummy. As shown in Figure 5, the laser head dummy is attached on top of the BCDS dummy. The ST is aligned onto the reference target mirror. The mirror is removed and the 4DAD is then used for recording the alignment reference coordinates. The angular projected cross becomes visible onto the CCD when ST is set to infinity as seen in Figure 6 and the lateral projected cross becomes visible on the CCD when the ST is focusing onto the CCD as seen in Figure 7.

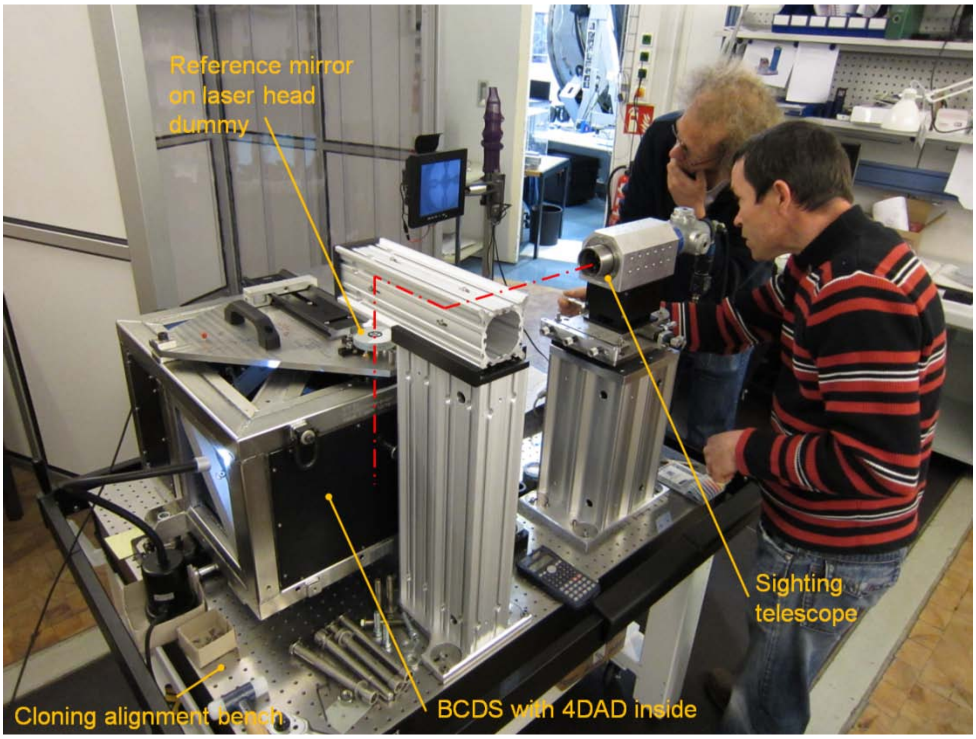

Figure 5: 4DAD referencing

7.2 White light from alignment telescope - low power calibration

The pre-calibrated collimated beam from the sighting telescope, using the laser head dummy reference mirror, projects a cross with the help of the focusing lens in the 4DAD onto the CCD and creates an image for beam pointing to result in two angular reference coordinates as shown in Figure 6.

Figure 7 shows the lateral coordinates which are derived from ST in imaging mode using the beam profiler (no powered optics in 4DAD path for lateral reference)

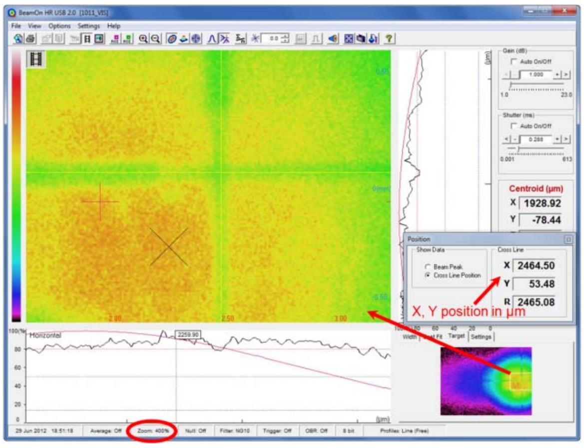

Figure 6: Angular displacement, reading to be converted

1 µm = 0.4 arcsec

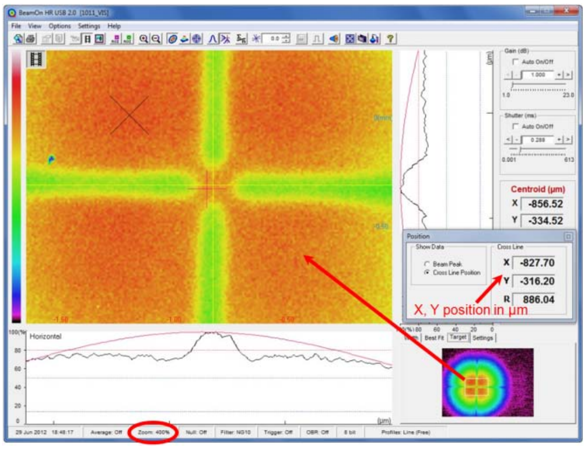

Figure 7: Lateral displacement, direct reading

Reference recording accuracy has been estimated to 1 pixel for both angular and lateral position i.e.:

- Lateral referencing accuracy: 5 µm
- Angular referencing accuracy: 2 arcsec

7.3 Narrow band 20W laser @ 589 nm recording

Both optical paths are displayed together in one frame as shown on Figure 8. The collimated large beam gives lateral beam pointing through automatic centroiding. The focused beam results in angular beam pointing information through centroiding. Laser waist location is for the 4LGSF laser near the beam splitter, so that no cross-talk between the two measurements is expected. The ellipsoidal shaped laser beam in the lateral displacement beam is presumably the result of different polarization properties in the optics. An improvement is currently under investigation. However for the main requirements of centroiding, this has no effect.

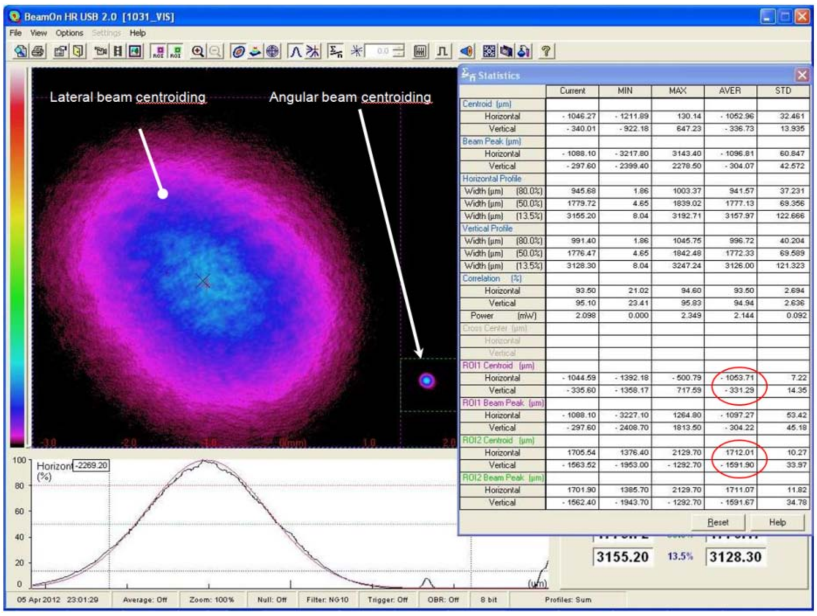

Figure 8: Single frame with lateral and angular position centroiding recording of a 20W laser @ CW 589nm.

8. CONCLUSION AND FUTUR TESTS

4DAD fulfills all the original requirements and allows high resolution beam pointing lateral and angular recording in a fairly compact device. This is particularly not common for a device or measurement system, which covers such wide light intensity range without any configuration change.
One clone unit is foreseen to be built that provides the same calibration approach and that is based on the common reference laser head dummy. This second unit will be used on site at Paranal in Chile to check laser head alignment after transport while the first one will be used in Europe for aligning the remaining laser heads.

Further tests are foreseen to fulfill additional requirements which are:

- Calibrated pointing model for laser beam stability recording under various inclination (+/-90°)
- Calibrated pointing model for laser beam stability recording under various steady temperature (1 to 15°C)

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