The RASNIK 3-point alignment monitor system

Niels van Bakel[a], Mark Beker[a], Gerjan Bobbink[a], Bram Bouwens[a], Rogier van der Geer[a], Harry van der Graaf[a], Henk Groenstege[a], Robert Hart[a], Kevan Hashemi[b], Joris van Heijningen[a], Marc Kea[e], Xaveer Leijtens[f], Frank Linde[a], Joseph A. Paradiso[c], Martin Woudstra[d]

a) Nikhef, Sciene Park 105, Amsterdam, The Netherlands
b) Brandeis University, Boston, Mass, USA
c) M.I.T., Cambridge, Mass, USA
d) Now at CERN, Geneva, Switzerland
e) Now at ASML, The Netherlands
f) Now at TU Eindhoven, The Netherlands

Abstract
The Rasnik alignment system, initiated in 1983, was developed initially for the monitoring of the alignment of the muon chambers of the L_3 Muon Spectrometer. Since then, the development continued since new electro-optical components became available. This paper is an overview of the technical developments.

Introduction

The momentum of a charged particle can be measured by recording the radius-of-curvature of its track, related to the Lorentz force due to the local magnetic field. The radius-of-curvature is defined by three or more points of the track. In practice, the track position points are obtained from three position-sensitive detectors, placed at a certain mutual distance, in the track space. For high momentum tracks, the curvature is small and the momentum is related to the 'sagitta', being the distance between the central track point and the line through the two outer measured track positions (see fig 1). The uncertainty on the momentum measurement of the particle is directly related to a) the intrinsic precision of the position sensitive detectors and b) the precision on the relative location of these detectors. Intrinsic position measurement accuracies of 10 - 50 μm are realized with e.g. silicon strip detectors or Multi Wire Proportional Chambers (MWPCs). Comparable precision and stability of alignment over distances larger than 1 m is notoriously difficult. Until 1983, accurate alignment could be achieved by applying a stretched wire as reference, and by a Taylor Hobson telescope [1], but these systems could not be applied as alignment monitors following real-time variations in alignment.
In 1983, an opto-electronic alignment monitor system, earlier proposed in a ham radio magazine, was of interest for Draper Laboratories for monitoring the actual geometry of the Space Shuttle's Robotic Arm [2]. The concept of this system, consisting merely of a light source, a lens and a 'four quadrant' light sensor, was evaluated at Nikhef, and a readout system, based on phase detection, was developed. A few hundred of these 'Red Alignment System NIKhef 'RASNIK' systems were applied in the L3 experiment [3], not only for monitoring the alignment of the tracking detectors, but, even in larger numbers, for the monitoring of the geometry (notably sag) of the muon tracking chambers.
In 1990, during concept studies for SSC and LHC experiments, the need for low-cost alignment monitor systems with a wider operation range became apparent. By replacing the four-quadrant diode by the then available CCD, the range of the system was not anymore limited by the size of the optical sensor, and the precision was greatly improved. Some 6000 of these systems we applied in the ATLAS experiment [4], and in other (possible non HEP) experiments. Recently, the Rasnik systems and some derives are commercially employed.

Chapter 1: Three basic systems

The Four Quad Diode ‘4QD’ Rasnik system

The system includes three components: a light source, a lens and a four-quadrant (4Q) photo diode. The lens projects the image of the light source onto the four-quadrant diode. The ratios of the four currents are functions of the displacement of the centre-of-gravity of the light spot and the optical centre of the 4QD sensor. (see fig 2).
For the Muon Spectrometer of the L3 experiment at CERN, 172 of these 4QD systems were realized. The light source consisted of a red LED with opaque layer, covered with a (photographic) mask with a transparent square. The opaque layer converts the LED into a Lambert radiator [5] resulting in a homogeneous light intensity within the projected spot on the 4Q sensor.
The lens is placed, in the direction of the optical axis, in the centre between light source and light sensor. Since the distance between light sensor and sensor was fixed at 5016 mm, special plano-convex singlet lenses were made with a focal length of 1254 mm, given the (narrow band) wave length λ of 850 nm. The lens diameter of 50 mm was found empirically to be large enough for an adequate signal-to-noise ratio.
As four quadrant sensor the EG&G ??? was applied: see fig 3. The dimension of the 4QD sensor determines the *range of measurement* of the system: with equal spot and 4QD size, both the transversal (X and Y) displacements of the image on the sensor equal half this size, in terms of spot displacement on the sensor. With a ratio of image and lens displacements of 2, the range of transverse lens displacements equals a quarter of the 4QD sensor.
The 4QD systems displayed a good spatial resolution, and their performance was intensely tested. First, thermal gradients in the ambient air, and fluctuation in air density due to convection needed to be reduced by means of shielding. For this, 2.5 m long aluminium tubes were placed in the light beams between sensor and lens, and lens and light source. An RMS of typical 3 μm was achieved in both the X and Y coordinate (expressed as image position on sensor), averaging measurements over 5 s. With (TL light) lab illumination on, a 100 Hz signal appeared on the analog quadrant outputs with an amplitude much larger than the 53 kHz system signal, increasing the output noise level slightly. Running two systems in parallel, with tightly coupled components closely spaced, the absence of drift has been confirmend. Since only one ADC is used for the readout of all quadrants, the only sources of 1/f noise are the resistors determining the gain of the analog quadrant preamps, and the 1/f noise of the quadrants themselves.
The precision of the 4QD system was measured by recording the calculated image position after displacing the sensor in well-defined steps. Deviations from the ideal system were due to:

- Imperfections of lens: non-sphericality, off-nominal focal length
- reduction of image sharpness due to diffraction
- non-homogeneity of light intensity of LED surface (due to geometry of the LED)

Deviations up to 15 μm were found within the range of operation. By means of a 2D scan, the deviations could have been recorded and stored as calibration data. Since the deviations were quite systematic for all systems, a 2-parameter correction was applied, common for all systems:

$$X_{corr} = aX + bX^3,\ \ Y_{corr} = aY + bY^3,$$

limiting the error to 5 μm for all systems, without individual calibration [6].

The CCD Rasnik system

For the ATLAS experiment[*], new requirements for the monitoring of the alignment of the chambers of the Muon Spectrometer, and for the monitoring of the chamber geometry, were formulated. The chambers were to be mounted onto the barrel toroids, and mechanical deformations due to magnetic forces could result in changes in chamber alignment up to 2 mm. The range of the alignment monitors should therefore be increased to 5 mm (in terms of light spot displacement on image sensor). This would require a 4QD with outer dimension of 10 mm x 10 mm, and a homogeneous light source with equal dimensions. The latter has been realised by combining a light guide and a specially shaped diffusor [7], but the large 4QD would have been too expensive. Instead, CCDs and CMOS pixel image sensors then became recently available. By applying a coded mask as light source, a section of this mask is projected by the lens onto the CCD. With adequate coding of the mask, the section is unique, and the range of the alignment system is no longer determined by the dimensions of the image sensor, but only by the size of the coded mask.
The image, after analysis, contains information of the X and Y coordinates of its position on the image sensor. The image scale can be determined, and therefore the ratio of the image distance and the object distance. With this, the 3rd (Z) coordinate of either the sensor, lens, or mask, with respect to the other two, can be recorded. In addition, the relative rotation of mask and sensor around the optical (Z) axis follows from the image data. A CCD-Rasnik system thus measures four degrees of freedom[+].
The essential component of the light source of a CCD-Rasnik system is the coded mask. Each contour (black-white transition) contributes to the information about the image position in the direction perpendicular to the contour direction. With the ‘dart’ mask (see fig 4), first results were obtained, confirming the wide range and high precision of the system: an RMS of X and Y coordinates better than 2 μm was measured [8]. Away from its centre, this masks has contours in only one direction, and the performance of the system would be worse. Instead, the coding should be such that the performance is equal over the entire mask. A better mask was based on the bar code pattern, in which the ‘vertical’ code consisted of the logical NAND of both the codes with vertical and horizontal bars: see fig 5 [9].
It is obvious that the total contour length, included in the image, should be maximised, and that the effective contour length in one direction should about be equal to the corresponding length of the orthonormal contour. A chess field pattern is the best solution for this, although an image, displaying a section of such a mask, is not different from another section. By coding the chess fields of the n^{th} row and m^{th} column, the ‘coarse’ position of the mask section can be defined, while the positions

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[*] The CCD-Rasnik system was initiated for the EAGLE and ASCOTT initiatives, which merged into the ATLAS collaboration.

[+] For CCD-Rasnik systems with a short distance between image sensor and mask, a mask rotation over its X and Y axii results in a gradient of the image scale over the image. With these ‘proximity’ systems, 6 degrees of freedom can be measured [k].

of all the vertical and horizontal contours (forming a continues grid) defines the fine position of the image on the pixel sensor: see fig 6.
The size of a chess field determines the total contour length in an image, and it's minimum is set by the Modulation Transfer Function (MTF) of the optical projection by the lens on the pixel sensor. Mask were made with a chess field size of 30, 60, 120, 170, 240, 600 and 1000 µm, always coarse-coded in the 9th row and 9th column. The high-precision masks were obtained from the photolithographic industry. Low-cost contact copies, maintaining precision, were used for mass production.
For the back-illumination of the masks, two principles are possible: the opaque Lambert radiator illuminated by one or more LEDs, and the application of condenser lens with one LED in its focal point. Instead of a condenser lens, a light and low-cost Fresnel lens may be applied: see fig 7. The diffusor type is simple, but emits little light due to its Lambert properties. The condenser types require only one (power) LED, but this LED must be carefully positioned.
The wavelength λ of the LED(s) may be chosen principally small in order to reduce image blurring due to optical diffraction. Since sub-µm precision is easily reached with larger wavelengths, infra-red LEDs were often applied, enabling shielding the image sensors against daylight [10]. In other cases, the wavelength may be chosen such that the effective focal length of the projecting central lens matches the actual object and image distances of the system.
First, the image sensor Philips VCM 3250 was applied, read out by a frame grabber in a pc. Some 5000 'RasCam' image sensors, based on the Vision VV5430 were developed for the ATLAS Muon Spectrometer, and a multiplexing video readout system was developed [11]. Since the X-coordinate of an image-on-sensor depends on the synchronisation of the video source with the frame grabber, special care was taken during the calibration of the systems to eliminate this potential error. Since 2000 (?), the active board of webcams is used, simply read out via USB.
The image sensor of a CCD-Rasnik system is not a critical component. A larger sensor surface provides more info, but in practice a sensor of 2 mm x 3 mm is adequate. The pixel pitch should be smaller than the diffraction effect (100 µm), and even the simplest webcam has much smaller pixels. The very large number of pixels in a webcam sensor, however, does not impose a disadvantage.

The RasDif system

For the alignment of active beam elements of future CLIC and ILC linear accelerators, systems with a distance L between the image sensor and the mask of a CCD-Rasnik system larger than 20 m are required. The diameter of the required lens becomes unpractically large, and its replacement by a Fresnel zone plate in the form of a photographic mask was considered. In an even simpeler 'RasDif' system, the back-illuminated coded mask would be replaced by a monochromatic point-like light source. A diffraction pattern, defined by the geometry of the Fresnel zone plate, appears on the image sensor, and the position of this pattern on the sensor is a measure for the alignment of three points, as in the CCD-Rasnik system, albeit that the scale of the image is proportional to the image distance instead of being equal to the ratio of the image and object distances.
Two parallel RasDif systems, shown in fig 8, were set up at CERN consisting of two stabilized HeNe lasers and two image sensors (Allied Vision Pike F100B) placed at 140 m distance, with a diffraction plate as depicted in fig 9 in between. The systems

were placed in a tube, reaching a vacuum of 10^{-6} mbar. At regular distances, light blocking 'field stops' were placed, reducing coherent background light (see fig 10). The images were as expected (see fig 11), indicating that the coherence length of the laser appeared to be sufficient, and that the illumination onto the diffraction plate was sufficiently homogeneous. The readout of a RasDif system is defined as the displacement, in X and Y of the diffraction pattern, on the sensor with respect to the pattern position at the start of a readout sequence.
With this setup, the application of RasDif as sensor for low-frequency seismic waves was tested, exploring its extremely low 1/f noise. The performance of the two parallel systems, discussed in (Chapter 4: Image analysis and error analysis) follows from the differential data of the two coupled, parallel systems. [12,13,14].

Chapter 2: The Components

The light source for 4QD systems

This light source should be bright, homogeneous, and have a well-defined geometry. In 1980, the brightest LEDs were red. Large area LEDs had an opaque layer, and the geometry of a single LED light source was well defined by masking the opaque layer with a transparent square in the form of a photographic negative.

The light source for CCD-Rasnik systems

The Rasnik light source is basically a light-emitting object. In its simplest form it consist of a black-white pattern, printed on paper, illuminated by daylight (fig 12). For smaller light sources, the precision of the position of the black-white transitions (contours) is essential: high-precision coded masks are realized commercially by e-beam photolithography on glass: contact copies cost less than 1 €/cm^2. Template 4" square masks of 85, 120, 170, 240, 600, 1000 µm chess field pitch were made available, facilitation Rasnik systems with image scales varying from 0.25 to 4.
For the back-illumination of a glass mask one ore more LEDs are applied. For the in-plane systems of ATLAS [4], a diffusor (Opaline) was applied to create a homogeneous illumination. This diffusor was a Lambert radiator [5], necessary in the case of multiple line-of-sights.
The diffusor was illuminated with a 3 x 3 array of LEDs (type??): radiation hardness tests showed that they could withstand a thermal neutron dose of 10^{15} n/cm^2, which were selected after radiation hardness tests [15]. The infra-red LEDs had a wavelength of 875 (?) nm: by appling a color-glass filter [10] in front of the sensor, background light could be shielded.
By selecting the wavelength of the LED, the focussing of a Rasnik system with a specific lens can be adjusted: for BK7 glass, the focal distance varies 4 % using light with λ from 0.4 µm to 0.8 µm.
If a light source is only used for one line-of-sight, then its light can be beamed into one direction, and sufficient intensity can be achieved using a single LED placed in the focus of a condenser or a Fresnel lens. An intense beam can be obtained, but it requires careful alignment of the LED, condensor lens and Rasnik lens, and the allowed rotation around the X and Y axii of the light source is limited.

The light source for RasDif systems

The coherence length of the light source should be larger than the length of the system, and using a laser is obvious. The divergence of the beam should be such that spherical waves arrive at the diffraction plate, with their apparent point of creation at least close to the laser (Z) position. In the case of a waisted beam, a scale factor is introduced in the change of alignment and the measured displacement of the diffraction pattern on the sensor. This results in a systematic error if the beam parameters are not stable.
For the seismic sensor setup at CERN [13], two stabilized HeNe lasers (Melles Griot 05-LHR-925) were applied. The position of the beam, in X and Y, relative to the laser tube varied by a micron, exceeding the potential system resolution of 10 nm. This was solved by coupling the laser by means of an optical fibre and in- and outcouplers: see fig 13. A variation of the beam position can only cause a variation in the beam amplitude in the vacuum tube, not affecting the measurement of alignment. In addition, the beam parameters could be tuned by the outcoupler adjustment.

Recently low-cost Diode Pumped Solid State (DPSS) lasers became available: their coherence length exceeds 140 m, but their lifetime and power stability may still limit their application.

The Lens (for 4QD and CCD-Rasnik systems)
The lens of a monochrome CCD-Rasnik system may be a simple spherical plano-convex singlet. Its focal length equals ¼ of the distance between light source and sensor, assuming equal object- and image distances. A large diameter (small aperture) favours the light yield on the image pixel sensor, reducing the effects of pixel noise and background light, and reduces image blurring due to diffraction. In addition, the larger field of view reduces the influence of fluctuations in the density of the air. Disadvantages of large diameter lenses are costs, the larger space required for the light beam, and the smaller depth-of-field of the system, possibly imposing tighter tolerances in the object and image distances. A very large diameter causes non-linearity's in the image (pincushion effect), to be avoided. In practice, for CCD-Rasnik systems with centered lens (scale S = 1), the lens diameter D equals about 1 % of the distance L between mask and sensor. For such systems, the image light intensity is equal, and the diffraction effect is in the order of λ . L/D = 100 μm, allowing the projection of tens of contours onto a pixel sensor area of 3 mm x 2 mm. If the Z position of the image sensor or the mask can be adjusted, low-cost standard series plano-convex lenses can be applied [16]. If the position of the image sensor and the mask is defined and fixed by the geometry of the object(s) to be monitored, expensive lenses with a specific focal length must be made. The depth-of-field equals +/- 10 mm for standard systems, setting the tolerance of the focal length for geometry-fixed systems [17].
If single LEDs emit rather monochromatic light, singlet lenses can be applied: otherwise achromats should be used. Some tuning of the effective focal length is possible by choosing a LED with a specific wavelength.
The image sharpness of a well-focused CCD-Rasnik system is diffraction limited, and the quality of the lens may be chosen accordingly.

Diffraction plate (RasDif)
The performance of RasDif systems is determined by the precision of which the (change of the) position of the diffraction pattern on the sensor can be established, discarding other external error sources. Ultimately, this precision is determined by the noise in the image pixels, and can be estimated with the Cramer-Rao Lower Bounds (CRLB) [18]. In the first RasDif systems, the pattern of transparency was a circle, and the plate had a simple hole: the diffraction pattern on the sensor is shown in fig. 14. The intensity of the light is high in the centre, and decreases rapidly away from the centre. The ring-shaped pattern (a) in fig 15 has a more evenly distribution of light and has a lower CRLB. The conclusion is that the choice of the pattern is only critical if sub-nm precision is required.
Where the range of a CCD-Rasnik system is determined only by the size of the coded mask, the range of operation of a RasDif system depends on the capability of pattern recognition in areas away from the pattern's centre. This may impose more stringent boundary conditions to the design of a diffraction plate.

The image (pixel) sensor

The sensor for the 4QD-Rasnik systems consist of four individual photodiodes, closely spaced in the “four quadrant” geometry. It could be considered as a 4-pixel array. For the L3 experiment, a special readout system for 4QD-Rasniks has been developed (see fig 16). The currents from the four quadrants were amplified and fed into an analog multiplexing readout system. The influence of (periodically variable) background light and drift in the preamp offsets was reduced by applying an inverting-mode amplifier, in phase with the LEDs being modulated at 53 kHz. The output of the inverting amplifier was digitized: the current through a dynode is proportional to the difference in the digital response with LED-on and LED-off. The position of the light spot on the sensor is calculated from the ratios of the four digital values of the quadrant currents. For this phase detection system the influence of background light is extremely small: only some Gaussian noise is superimposed. Since only one ADC is applied, the drift of the system (1/f noise) is smaller than can be measured.

After 1985, low-cost monolithic CCD and CMOS pixel light sensors became available, mainly employed in video cameras. These formed the basis for the CCD-Rasnik systems: in the first setup the Philips VCM 3250 was applied. The video signal was processed by means of a frame grabber, and images were stored on disk and analysed later off-line. For the 6000 Rasnik systems in the ATLAS experiment, the Vision VV5430 CMOS pixel chip was applied. The video signals were processed, after a hierarchy of multiplexers, by frame grabbers (Data Translation DT31xx series). Special care was addressed to the synchronisation of the video signals and the frame grabber, since the X position of an image depends critically on timing of the line sync signals. After 1995, the pc’s hosting the frame grabber were capable to analyse the images real time. Since 2005, webcams are available, and their pixel sensor board, read out by a pc via USB, is a perfect and low cost image sensor.

For application in particle physics experiments, radiation damage must be considered. For the ATLAS experiment, radiation hardness measurements were carried out in several facilities, testing light sources (LEDs) and pixel sensor boards: results are summerized, for instance, in the ATLAS documentation [15].

Chapter 3: Image analysis and error analysis

In the image analysis, the image data is processed, with relevant parameters as output data. These parameters are: the ‘horizontal’ X position of the image on the sensor (with respect to a specific reference), the ‘vertical Y position, the image rotation around the optical (Z) axis, and the scale (magnification) of the image. In addition, additional image information can be extracted, such as the total light and image sharpness.
The algorithm for the 4-pixel images of a 4QD-Rasnik system is determined by the geometry of the 4QD sensor (quadrant size, gap between quadrants) and the (projected) dimension of the light source. The precision of the 4QD system was measured by recording the calculated image position after displacing the sensor in well-defined steps. Deviations from the ideal system were due to: 1) imperfections of lens: non-sphericality, off-nominal focal length; 2) image blurring due to diffraction and 3) non-homogeneity of light intensity of LED surface.
Deviations up to 15 µm were found within the range of operation. By means of a 2D scan, the deviations could have been recorded and stored as calibration data. Since the deviations were quite systematic for all systems, a 2-parameter correction was applied, common for all systems:

$$X_{corr} = aX + bX^3, \quad Y_{corr} = aY + bY^3,$$

limiting the error to 5 µm for all systems, without individual calibration [6].

For the CCD-Rasnik system, the first algorithm was based on minimizing the summed squared differences in pixel content between the image to be analysed and a simulated image. The simulated image (see fig 4) data was calculated with the centre of the dart pattern as input parameters (X_{cen},Y_{cen}). With this algorithm, the good performance of the CCD-Rasnik system was demonstrated, albeit that the process was not automatic, and extremely slow.
After the introduction of the ChessField mask, the **Linde-Woudstra** algorithm was developed. (?Frank, please check and modify what follows?). First, the position of horizontal and vertical black-white transitions (contours) were calculated by differentiating the row data horizontally and the column data vertically (see fig 17). From this, three parameters of the set of vertical contours can be derived: 1) the horizontal position (X), 2) the rotation around the optical Z axis (rotZ), and 3) the pitch of the vertical contours (dX). After this, the corresponding parameters Y, rotZ and dY were calculated from the horizontal contours. The consistency of the parameters rotZ (2x) and the dX and dY is a measure for the precision of the ChessField mask, the sensor, and of the algorithm itself. The total set of 6 parameters determines the orthonormal grid formed by all the contours. This grid data determines the *fine* output coordinates X, Y, Scale and rotZ. The *coarse* X and Y follows from the determination of the coarse data bits presented in the 9th row and 9th column, which can be found quickly since some of these (dark or light) chess fields do not have the opposite (light or dark) neighbours above, below, left and right. The coarse code, both for the X and Y coordinates, is redundantly present in an image. By applying ‘majority logic’ routines, the image analysis routine can be made robust against large dust particles or other image corruptors like shadows caused by cables in the light path.

For a standard CCD-Rasnik system, the total vertical and horizontal contour length on the sensor is about 100 mm. For a sensor with 10 μm pixels, the position of this contour is measured 10.000 times with a set of ~ 5 pixels with content varying from light to dark, contributing to the contour position data. The ultimate precision of the X and Y coordinate of a CCD-Rasnik system can be obtained from the Cramer-Rao estimator, and has a value of 1 – 10 nm [13]. In a CCD-Rasnik setup, the mechanical stability, and the propagation of light through the ambient air frustrates the measurement to this precision. The performance of the image analysis routine was therefore tested with data from a system on which the ChessField mask was mounted directly on the sensor, illuminated from a point-like light source placed at a meter distance. The shadow of the mask created a typical shadow image on the sensor. Here, the alignment of sensor, mask and light source is of little influence of the image position of the sensor. The precision of the contour positions of the ChessField mask are known better than 10 nm, and the variation in pixel dimensions and pixel pitch of the sensor is of the same order of magnitude. With this set-up, the pixel pitch of a sensor can be measured accurately. Variations of 20 nm in X and Y, and of 10^{-5} of the image scale, have been recorded. These values are larger than the Cramer-Rao estimator, possible due to differential thermal expansion effects of the mask and sensor, and variations in alignment.

The image scale is determined from the X and Y pitch of the contour grid: the weight of a contour increases linearly with its distance to the centre of the image.

In the **Hashemi** algorithm, the differentiation of an image row or column, as shown in fig 17, is replaced by a Fourier transformation [19].

The **FOAM** algorithm was originally developed for the analysis of diffraction pattern images of RasDif systems, as shown in fig 19 [12]. The image shift is obtained from the change in the 2D phase image with respect to the reference image. For the latter, the first image of a data run is often applied. Essentially, FOAM outputs the displacement of the diffraction pattern on the sensor. This displacement does not depend on the pattern itself: the diffraction pattern is only supposed not to change.

Fig 20 shows a typical 2D Fourier power spectrum of a typical Rasnik ChessField image. The 2D peak information determines the X and Y pitches of the contour grid, and the fine position of the grid follows from the phase diagram [20a]. The performance of FOAM is published in [20].

Chapter 4: Calibration

A Rasnik system may be mounted on an object with known geometry; for instance on a detector during its construction on a granite table. The calibration of a Rasnik system is then reduced to the recording of the readout data during the period that the detector has this (known) shape. Later, when operational, the change of geometry (i.e. chamber sag) follows from the comparison of the actual readout data to the calibration data. In general, there are two calibration parameters in linear systems: slope and pedestal. The pedestal is obtained, in this case, during the construction; the slope is determined by the scale of the mask (which is very well known) and the scale of the sensor (known or to be measured precisely).

In principle, the three components of a Rasnik system could each be equipped with a mechanical reference in X and Y. These planes have a well-defined distance to the optical centre of the sensor, mask or light source, and lens or diffraction plate. This is quite unpractical: the location of the optical centre of a lens is, for instance, hard to define. Moreover, one needs to know the combined offsets, and not necessarily the offsets of three components.

An elegant and efficient way of calibration is possible by applying Rasnik systems with their excellent stability (constant offset) and linearity (constant and precisely known slope) [3]. The principle of such a calibration system is depicted in fig 21. It consists of a station, acting as support for the three components, and three precisely identical gauge blocks carrying three Rasnik components, respectively. After placing the three gauge blocks on the station, the Rasnik system will have certain readout values. Then all three gauge blocks are rotated by 180 deg around the optical axis. If the alignment of the station is perfect, then there will no change in the readout values. A deviation of perfect alignment, expressed in a variation δ of the middle component with respect to the outer components (see fig 21) results in an image shift on the sensor of 4 δ. After one rotation, the alignment of the station is known, as well as the 'calibration' value of the Rasnik system on the gauge blocks, being the average of the two, and equal to the reading when placed on a perfectly aligned station. With known alignment of the station, a large number of 'production' systems can be calibrated rapidly.

For the ATLAS Muon spectrometer, the 'projective' Rasnik systems were calibrated on a steel bar as station, with supports and gauge blocks shown in fig 22. Redundancy in the calibration values suggested a total error of 2 μm, which is well explained by the mechanical tolerance in a hole-sphere definition. Calibration values measured two years later were consistent [21].

Chapter 5: Applications

For the Muon Spectrometer of the L3 experiment, 272 4QD-Rasnik systems were applied [3]. For ATLAS, some 6000 CCD-Rasnik systems are operational [4]. These systems are also applied in CMS [CMS], CDF [CDF], HADES [HADES], LHCb [LHCb] and Visir (Visir).
For the ATLAS experiment, some variations on the CCD-Rasnik systems were developed. By fixing the lens and image sensor in one mount (forming a camera), the translation of the (illuminated) mask, in three dimensions, as well as its rotation around the optical axis of the camera, can be measured. These displacements can not be distinguished from a rotation of the camera, but in specific applications these rotations can be excluded. With their short distance between mask and camera, these **proximity** systems are high-precision, low-cost and contact, friction- free 4D feeler gauge: see fig 23. An even simpler device, consisting of a mere webcam and a (paper) coded mask pattern is shown in fig 12. With this, 4D mask displacements can be measured even at a larger distance from the camera, provided that the camera is fixed well. This system can be applied as n-point alignment systems by placing masks at several distances, in a row, parallel to the optical axis.
The Boston CCD Angle Monitor **BCAM** is a camera looking at more than one light source (see fig 24). With BCAM, the angular distances between the light sources, placed at different distances, can be measured. By combining the BCAM (photogrammetry) data with other alignment (possibly BCAM) data, 3D position data of the light sources is obtained [BCAM].
For most Rasnik systems, the precision is limited by variations in the density of the ambient air. A gradient in density causes light to deviate from a straight line. Since the index of refraction of air depends on the wavelength of the light, the bending of a light beam, and therefore eventually the image position, depends on the applied colour. In **color-Rasnik**, a three-color (webcam) sensor is applied, and a light source is used consisting of infra-red and ultra-violet LEDs, a diffusor and a mask. The difference δ in the positions of the UV and IR images is a measure for the bending of the light, and the 'straight' image position can be calculated (see fig 25). For dry air of 20 ^{o}C, the index of refraction equals $n_{\lambda=400} = 1.002817$ and $n_{\lambda=800} = 1.002748$ for wavelengths of 400 and 800 nm respectively. The position of the unaffected 'vacuum' image is located at $n_{\lambda=800} / (n_{\lambda=400} - n_{\lambda=800}) = 38 \cdot \delta$ below the affected image. The error of the correction is therefore a factor $38 \cdot \sqrt{2} = 54$ larger than the intrinsic image position error. In practice, this intrinsic error is much larger than the Cramer-Rao estimator since density fluctuations in the ambient air do not only cause an image shift, but also image distortion.
As stated in (4-Image analysis and error analysis**)**, the best possible precision of a Rasnik system is determined by the quantity of contour information on the image pixel sensor. A larger sensor area is therefore useful, unless the performance is limited to variations in the density of the ambient air. A large-area sensor can be obtained by combining two or more pixel sensors. By placing two pixel sensors at a certain distance (**Stereo-Rasnik**), the image scale S can be measured with high precision.
With the ultimate RasDif system placed on the **Moon**, seismic waves could be detected, possibly initiated by gravitational waves. The seismic noise level between Moonquakes (due to impacts and tidal deformation) is extremely small. Three RasDif components (light source, diffraction plate and image pixel sensor) could be installed, with a distance of ~ 20 km between light source and sensor. The Moon's vacuum is excellent in terms of not affecting the RasDif light beam. With a panel of 1 m^2 filled

with pixel optical sensors, the Cramer Rao estimator of the integrated image sensor could be well below a nm. With this system, the Moon's eigen-frequencies could be measured, and the effect of gravitational waves follow from (sudden) changes in the amplitude of these Moon Hum resonances [13].

Acknowledgements
We would like to thank Hans Post, Astrid van der Horst, Gerard Faber, Hans Postema, Paul Rewiersma[×], Sandro Sman, Jos Vermeulen, Ulrich Becker, Pieter Duinker, Marion White, Patricia McBride, James Branson, Jim Bensinger, Bianca Jongkind, A. Smeulders, Claude Guyot, Philipe Schune, Florian Bauer, Pierre-Francois Girod, Helene Mainaud-Durand, Tom Touze, for their contributions to the Rasnik alignment system.

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Enlarged linearity range of a Rasnik system using an integrating sphere

J. Alberdi[a], C. Burgos[a], A. Ferrando[a], , A. Molinero[a], V. Schvachkina[1, 1], C.F. Figueroa[b], F. Matorras[b], T. Rodrigo[b], I. Vila[b]
[a] CIEMAT[2], Edificio 2, Investigation Basica, Avda. Complutense 22, 28040 Madrid, Spain
[b] Universidad de Cantabria[3], Santander, Spain
http://dx.doi.org/10.1016/S0168-9002(98)00229-0, How to Cite or Link Using DOI