行政院所屬各機關出國報告

(出國類別: 考察)

赴歐洲考察精密儀器技術發展趨勢
出國報告

服務機關：行政院國家科學委員會精密儀器發展中心

出國人：

姓名	職稱
陳建人	主任
黃鼎名	研究員

出國地區：歐洲

出國期間：中華民國九十二年十月十一日至十月二十日

報告日期：中華民國九十二年十二月十日

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赴歐參加精密工程技術研討會

主辦機關:

行政院國家科學委員會精密儀器發展中心

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關鍵詞: 精密工程技術，光學元件，光學材料

內容摘要: 此次訪察行程共十天，造訪機構均位於德國且爲世界知名的光學原料及光學元件製造及檢測廠商，含OptoTech，LOH Optical Machinery，SCHOTT Glass，TRIOPTICS 及Moeller-Wedel Optical，行程相當緊湊。精密儀器發展中心以累積多年之光、機、電及儀器整合技術爲基礎，配合產學研各界的需求，擇定光學遙測技術、奈米及微系統技術爲長期發展項目。此行赴歐洲相關機構考察光電精密製造技術發展現況，目的在學習國外相關研發計畫之計畫訂定與管理、光學材料及光學元件之製造與檢測等諸多技術經驗之累積，提昇精密儀器技術水準，並掌握國際精密儀器發展趨勢，以作爲中心遙測計畫執行基礎及未來我國精密儀器產業技術發展之依據，以利遙測計畫之推行。

目錄

一、緣 起

光電產業為我國繼半導體產業後另一高科技、高成長產業，在相關產品如數位相機、光碟機、投影機等技術的不斷精進下，帶動了相關光學元件需求的快速成長，連帶使得台灣精密光學產業蓬勃發展；根據光電協進會 PIDA 的預估，未來幾年之精密光學元件市場需求值高於產值，所以國內精密光學元件廠商的未來幾年獲利成長性相當看好。而目前光電儀器或產品的研發已朝向輕、薄、短、小的概念發展，包含非球面光學元件的製造技術等。因此，即時掌握儀器技術的發展現況，將是帶動國內相關研究與技術發展之重要關鍵。

精密儀器發展中心以累積多年之光、機、電及儀器整合技術為基礎，配合產學研各界的需求，擇定光學遙測技術、奈米及微系統技術為長期發展項目。目前光學遙測計畫中規劃長期目標為高解析度光電遙測酬載(Remote Sensing Payload)的研製，目標在於自主研發與整測能力的建立，其中關鍵技術之一即為精密光學元件的製造與檢測，包括非球面製造檢測技術。

迄至目前為止德、法、美、日等國有較完整的光學製造與檢測儀器與技術，因此為提升本中心光學檢測與製作技術，並掌握國際精密光學儀器發展趨勢，以做為未來我國光學儀器產業技術發展之依據，赴德國相關產業機構考察光學製造檢測技術發展現況，蒐集相關光電產品與技術的發展訊息。

為求光電遙測酬載長期目標之順利達成，除已參與中華衛星二號之遙測酬載研製計畫，以吸取國外公司經驗。同時為提昇本中心精密光學元件製造檢測技術，已陸續擴充並添購相關儀器設備，本年度並採購了「偏位分析與組裝系統」

(Alignment & Assembly System)檢測設備，做為光學鏡片或系統組裝及檢測之用，本設備將於年底前運抵國內，利用此行也一併瞭解遙測計畫與光機實驗室所需組裝分析儀器並就相關技術問題與原廠工程師做研討。

二、考察目的

(一)考察精密光學元件檢測技術現況與發展

德國為現代光學工業的發源地，從玻璃材料、光學製造加工機至光學檢測儀器有一完整的工業體系，歷史悠久且不斷創新改良。Schott Glass 為世界知名玻璃材料供應商，除一般玻璃材料外，也製造適合太空使用之低膨脹係數玻璃 Zerodur，並進行玻璃材料性質檢驗；Trioptics GmbH 與 Moeller-Wedel Optical 均為德國以製造光學量測儀具起家的公司，其產品幾乎涵括所有光學元件量測、光機組裝檢測與分析設備，諸如有效焦長、曲率半徑、偏心量、稜鏡角度、折射率、光學調變函數(Modulation Transfer Function, MTF)及組裝偏位分析等的量測儀器產品齊全。藉由本次的參訪可以獲得相關玻璃材料及光學檢驗儀器產品資料與最新技術發展，除可就量測技術交換經驗心得外，並可與該公司工程師就精密光機量測儀器的設計與組裝等相關問題進行討論。

(二)了解新購 Trioptics 公司偏位分析與組裝系統組測情形

為提昇本中心精密光學元件製造檢測技術，自 89 年度起陸續擴充並添購相關製作與檢測儀器，包括非球面成型機、雷射定心機、非球面拋光機、輪廓儀與大口徑干涉儀等，建立起中心在精密光學元件製造上的優勢地位。

但目前本中心在光機組裝上，尚缺乏一套具精準組裝控制平台與軟體分析的設備，故本年度向德國 Trioptics 公司採購了「偏位分析與組裝系統」檢測設備，做為光機組件或系統檢測及組裝之用，本儀器採用非接觸方式量測光學鏡片或鏡組之定心與對準誤差，亦可應用於檢測完成組裝之鏡頭整體定心誤差、機械誤差、焦長、曲率等。本設備將於年底前

送交本中心使用，故赴德了解該儀器組裝與測試情形。

(三)考察精密光學元件製造儀器與加工技術

為建立高解像力光電遙測儀器研製自主技術能力，大口徑非球面鏡片的製作是一項關鍵的技術。本中心近年來致力於非球面鏡片的開發，雖已投入相當多的人力與經費，然近年來加工機具精度的不斷提昇與技術改良，已漸朝自動化加工與大量生產的方向邁進。

LOH Optical Machinery 與 OptoTech GmbH 均為德國境內著名光學鏡片加工機製造廠商，本中心目前也都購有該兩公司的加工與檢測機台，此行將前往該公司考察光學元件最新加工機與製造技術，除可與原廠技術人員就目前機具使用上問題討論外，大口徑鏡片研磨拋光的技術更是我們亟欲了解的課題。研製大口徑遙測鏡頭為本中心發展目標之一，藉由本次參訪機會，可以評估本中心在光學元件製造檢測上的能力指標，並就未來發展方向提供更清楚明確的藍圖。

(四)考察光學量測儀器申請 ISO 17025 認證評估方式

為提昇中心光學/光機檢測實驗室服務品質與運作效率，並建立產業對中心出具測試報告之公正性與專業性的信心，目前本中心規劃申請中華民國實驗室認證體系(Chinese National Laboratory Accreditation; CNLA)認可符合國際標準 ISO/IEC 17025 的光學測試實驗室，未來所簽發之測試報告，將可具國際認可標準與共通接受性，達到「tested once, accepted everywhere」之目標。

依規定，申請認證之測試項目所使用的儀器與方法都必須做量測不確定度(Uncertainty)的評估，惟國內目前對光學測試領域方面的量測不確定度評估相當缺乏，因此藉由本次參

訪這些知名光學量測儀器廠商，了解其是否有相關評估經驗或方法，這對未來申請認證工作有很直接的幫助。

(五)建立光機技術交流合作管道

光電產業為國內熱門產業，但目前光學設計、測試及光學機構人材較為缺乏，仍待培養，人材與經驗的缺乏將使得光電產業的發展受限，並使得關鍵技術或組件無法突破。而不管是 Trioptics、Moeller-Wedel Optical、Loh、Schott 或 OptoTech 等均在精密光學元件量測儀器與加工機製造上有相當的經驗與技術，若能與該公司建立起技術討論或交流管道，甚至利用互訪機會或是派遣專家來台研討，將對於本中心光機技術能力的提昇與未來發展將有正面積極的幫助。

三、過程

行程表

中華民國九十二年十月十一日至十月二十日，計十天

日期	起	至	工作內容	天次
10/11(六)	台北	法蘭克福	Taipei(23:00)✈Amsterdam(9:55)	1
10/12(日)			Amsterdam(13:15)✈ Frankfurt (15:05)	2
10/13(一)		法蘭克福	參訪 OptoTech 考察光學元件加工製造技術	3
10/14(二)		法蘭克福	參訪 Loh 考察光學元件加工製造技術	4
10/15(三)	法蘭克福	漢堡	參訪 Schott Glass 考察光學元件製造技術 Frankfurt (14:10)✈ Hamburg (15:10)	5
10/16(四)		漢堡	參訪 Trioptics 考察光學檢測儀器與技術	6
010/17(五)	漢堡	阿姆斯特丹	參訪 Moeller-Wedel Optical 考察光學檢測儀器與技術 Hamburg(14:25)✈ Amsterdam (15:20)	7
10/18(六)		阿姆斯特丹	資料整理與撰寫	8
10/19(日)	阿姆斯特丹	台北	搭機返國	9
10/20(一)			Amsterdam (12:35)✈ Taipei(11:05)	10

各考察行程細節如下所述：

（一）OptoTech 公司

OptoTech 公司位於德國中部法蘭克福附近，1985 年創立，為世界知名眼鏡鏡片加工與非球面加工與檢測專用機製造廠商，總員工數約 150 名，總部負責設計及產品組裝，元組件製造由分廠及合作廠商負責。本中心近年來致力於提升光學廠與機械廠加工與檢測技術的提升，先後引進了非球面拋光機、輪廓量測儀、CGH 干涉儀及 CNC 加工機，CGH 干涉儀即為該公司產品，用於檢測非球面之檢測。該儀器(如圖1.1)利用 CGH 干涉片修正非球面波前，其餘步驟與干涉儀檢測球面鏡相同

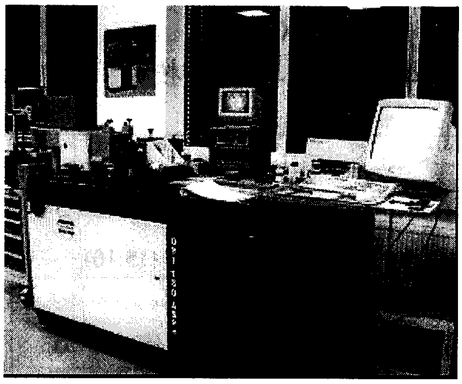



圖 1.1　CGH 干涉儀及 CGH 干涉片

除 CGH 干涉儀外，該公司現有球面成型機(由直徑 1 mm 至 500 mm)、非球面成形機(由直徑 10 mm 至 300 mm)、眼鏡鏡片加工機及柱面鏡拋光機，眼鏡鏡片也有專用加工機可代工切割客戶要求特殊形狀之拋光皮。產品組裝線上可看見滿載現象，平均現場有 10 台機台正在組裝，約花費 1 週時間可組裝完畢。客戶訓練有專用教室，在此之機台除做為展示訓練用，有時也用於新機台試驗用。

該公司目前非球面成型機最新機種為 ASM 300 CNC，可做球面、非球面成形及自由曲面(free form)加工；其加工直徑為 10mm-300mm，雙刀軸(twin cutter)可於同一加工製程中

完成粗磨(rough-grinding)及細磨(fine-grinding) (如圖 1.2)，其加工的精度為 0.001mm，該機台在成形非球面鏡片時，所輸入的參數不是像光學工廠現有成形機的點資料，該機台是直接輸入非球面參數：圓錐常數(Conic Constant)、中心曲率半徑(R_0)及高階項常數(A、B、C….)等三項，依廠商說法可得到較準確的非球面面形(Form)。

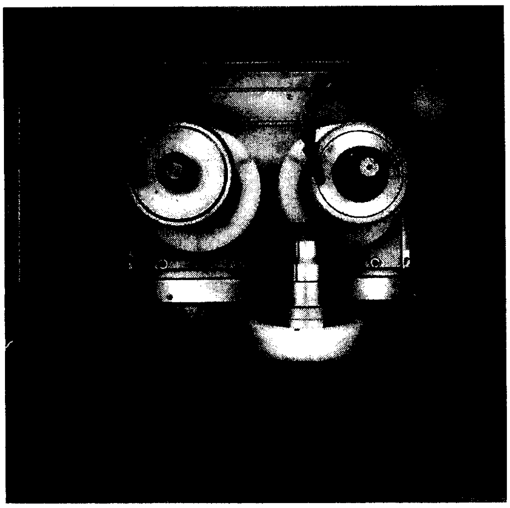


圖 1.2 twin cutter 加工概念

稜鏡成形機為 PKS 250 CNC (如圖 1.3)，可做稜鏡成形及任意曲面的修邊(Edging)，其最大加工尺寸為 250mm，其精度可達 1 分(1')，該機器除了可做稜鏡成形外，並可做任意外型包括直線、圓弧及自由曲面(Free form)的加工。

Opto Tech 公司在成形刀具的開發上也下了一番很大的功夫，他們開發在同一支刀具上同時有粗磨及細磨的鑽石磨輪(Diamond wheel cup)，他們稱為 Kombi-Technology，其外型(如圖 1.4)所示，粗磨的磨輪做的比較大，然後在粗磨輪的內部在裝上一具細磨輪，且刀具的控制完全由軟體控制，如此可消除因更換刀具所造成的誤差。

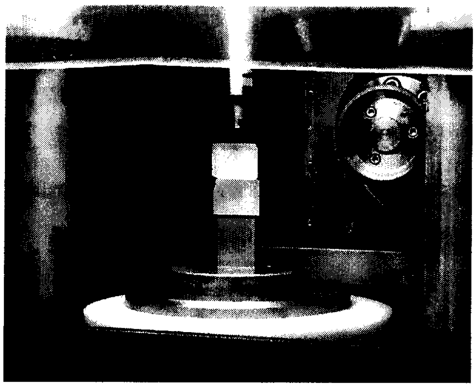


圖 1.3 PKS 250 CNC 稜鏡成形機

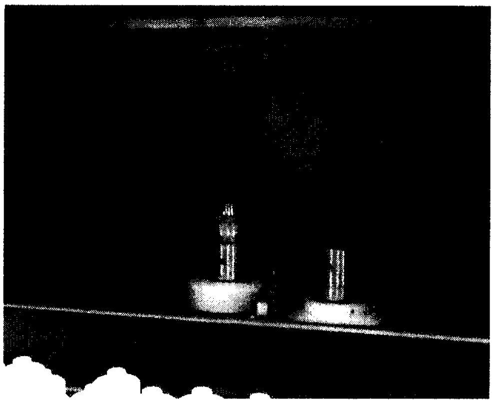


圖 1.4 Combi diamond wheel cup

關於非球面拋光，該公司也開發出一套拋光程序，利用一類似圓球物體，上貼拋光皮，利用二軸同時旋轉方式拋光，工具軸與工件軸成 90 度，工具軸相對於工件進行二個方向平移，如圖 1.5 左。拋光後經輪廓儀量測後取得需細拋光部份資料再以細拋光頭進行修正拋光，如圖 1.5 右。經上述方式可取得足夠面精度之非球面光學表面。利用此方法經試驗結果，面精度可由原先 P-V 值 1 μm 降至 0.3~0.5 μm。

輪廓量測在非球面加工相當重要，該公司利用接觸式量測原理也開發出一輪廓量測原型機，用於實際測試並做為實際生產前改善之用。

OptoTech 公司目前也與 Zeiss 合作開發大口徑非球面拋

光機，由 Zeiss 提出需求，OptoTech 設計並組裝原型機後交由 Zeiss 實際測試並將結果回饋給 OptoTech 做為下次設計改進的參考。此種方式不僅可將二家公司的專長合併，也將終端需求的機台開發出來，有助於提升二家公司的技術能量及產品競爭力。類似此類合作開發案值得我們效法，實際若在國內執行此類案件時最常遭遇的問題通常是非技術問題，如經費移撥、人員駐廠問題。

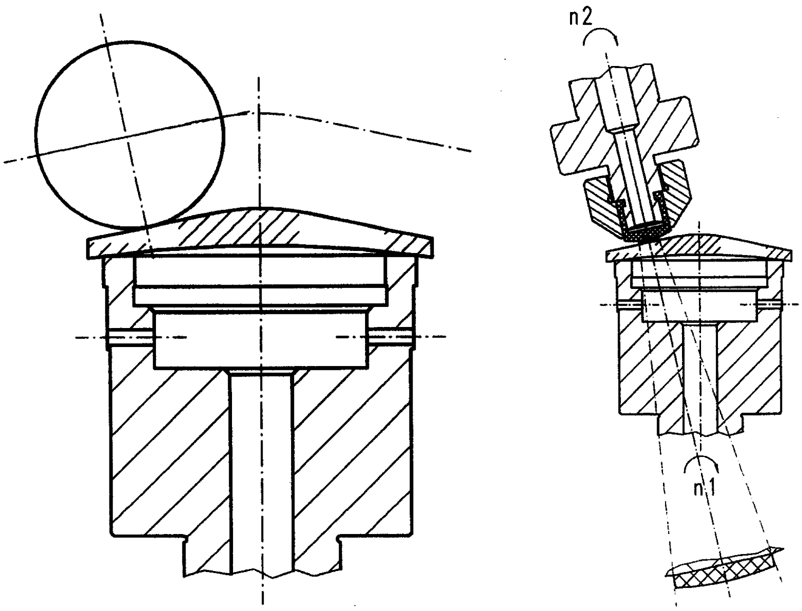
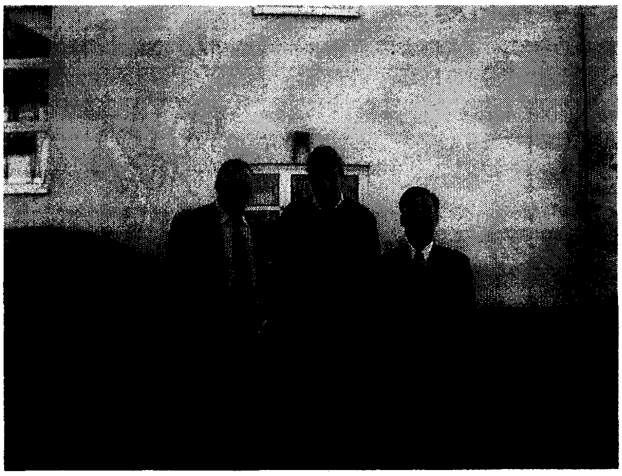


圖 1.5 非球面拋光與修正拋光概念

從參訪中可見到 OptoTech 公司開發之機台均有效利用 CNC 機台特性，利用電腦控制粗細磨出所需的輪廓，後由輪廓儀量出目前輪廓後，再經軟體自動修正需再細磨部份再進行拋光。此種 CNC 加工機其實與國內生產之機械工作母機有雷同之處，都需要穩定精密的平移與旋轉機構，較明顯不同處在於尚需一穩定之空氣軸承及針對光學元件加工所需之控制軟體。由此思考，若未來大口徑鏡片加工設備受限無法由國外取得，中心可以考慮與國內加工母機生產產商合

作，將雙方之專長合併，開發出適合的加工機台。

從參訪中也可感覺出，OptoTech 公司將大部份心力放置於機台機構及控制軟體，光學部份對其產生的困擾較少，因而得以將大部份心力用於改善機台穩定性及使用親和力上，此點與中心內將大部份心力用於光學設計及組裝方面有明顯不同。



（二）LOH Optical Machinery

LOH 公司也位於德國中部法蘭克福附近，OptoTech 公司即由部份 LOH 離職員工所創，因而該公司有較大之機台生產線(如圖 2.1)，甚至客戶所需之消耗品，如拋光皮、拋光粉、冷卻液等均有大量庫存，足以應付客戶需求。該公司產品線主要有眼鏡鏡片加工機台及精密光學元件加工機台，二者出貨量約一比一。中心曾引進該公司之定心機與雷射對心機，此次參訪主要在於觀摩瞭解非球面鏡製作之最新動態。

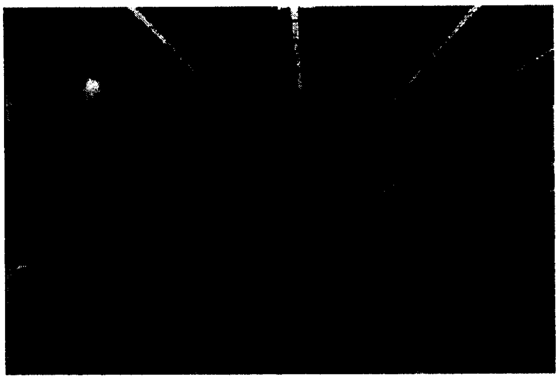


圖 2.1　LOH 公司產品生產線狀況

整體而言，LOH 與 OptoTech 生產機台之原理類似，包括眼鏡鏡片及精密光學元件機台外型及工作原理均非常神似，但二者使用之控制器及內部一些技術細節會略有不同。此外由於 OptoTech 加入競爭，LOH 也開始思考一些不同的生產機台，如近半球或大於半球玻璃鏡面成形技術(主要用於彈頭)，該技術概念利用一類似冰淇淋挖杓，一片一片向下挖，可成形所須之半球曲率，此方法也較傳統方法節省物料。

除上述外，LOH 也發展出一套接近全能加工機概念，可成形球面及非球面，成形平面，成形柱面鏡，切割稜鏡，鏡片外徑縮小，鏡片外邊形狀加工，鏡片階梯狀加工，鏡片導角等工作。主要原理在於利用多軸加工概念，如圖 2.2，上

二旋轉軸，可前後上下左右移動，提供球面或非球面粗磨及細磨成形，同時也可提供鏡片修邊、外徑修整等功能，此部份刀具可利用刀具庫概念，隨時更換所需的適當刀具。下方中間為工件夾持及旋轉軸，負責夾持工件並提供定位及旋轉功能，當成形鏡片時旋轉，當修整鏡片外型或稜鏡切割時也提供角度定位功能。下方左右還有另一旋轉軸，可帶動工件轉軸轉動至固定角度，鏡面成形或稜鏡切割時可變換角度，如圖 2.3 為稜鏡成形加工概念。

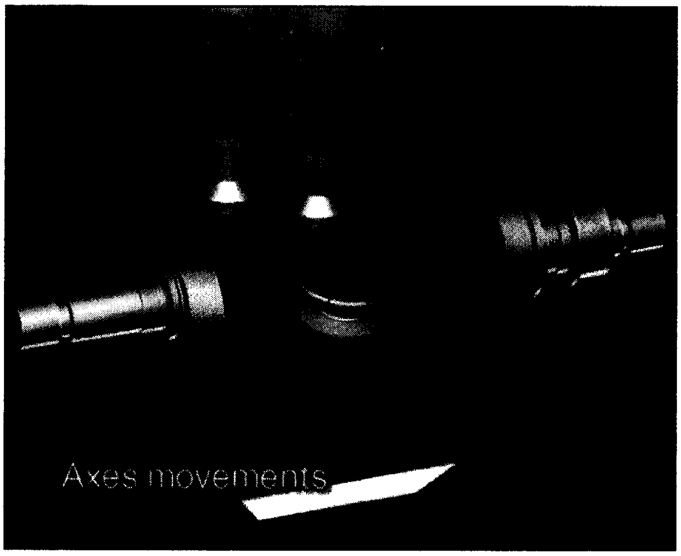


圖 2.2 多軸加工概念

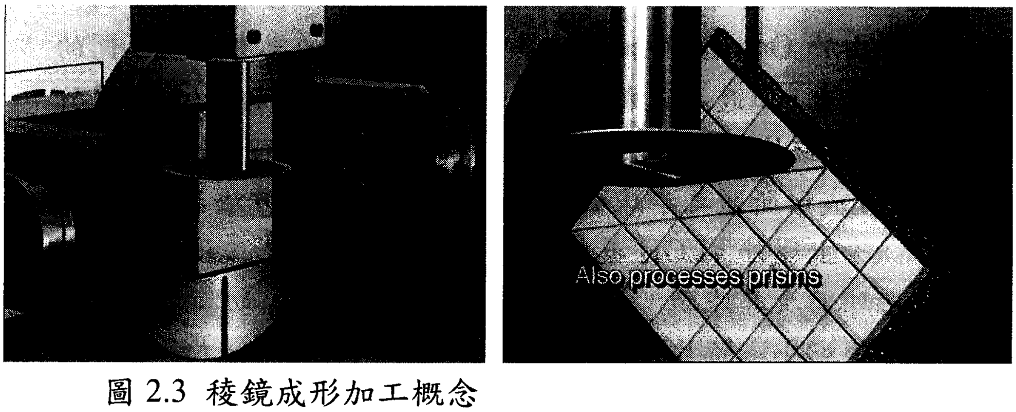


圖 2.3 稜鏡成形加工概念

近來由於 DVD 讀取頭及手機照相功能，小型非球面鏡片加工需求越來越多，該公司也將大型工作機台概念具體實際化成小鏡片加工機台(一般口徑由 1~25 mm)，圖 2.4 為小鏡片定心機，也使用雙面修整概念，但另加上一選項功能，可自動夾持工件由準備區至加工區域後至完成區。

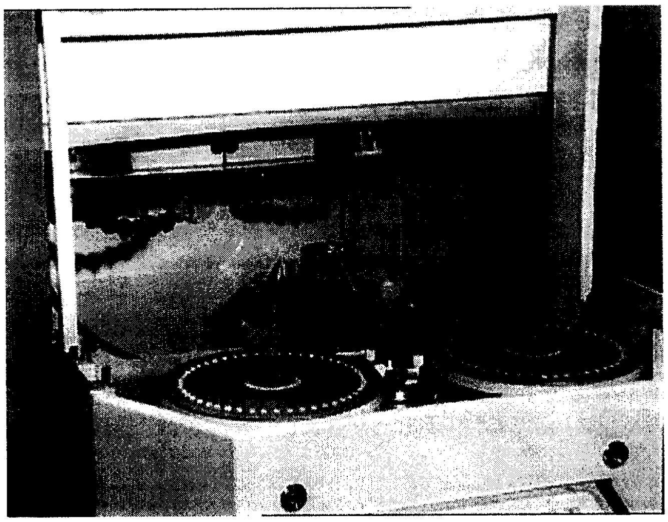


圖 2.4 小鏡片定心機

該公司內部也設有機械加工廠，工具機有傳統機台及 CNC 自動機台，這些機台有些生產機台組裝用零件，有些則生產夾治具零配件。無論現場組裝或機械加工人員，LOH 均有一套技術培訓計畫，合格者才能實際到現場加工或組裝，如此也確保製作及組裝品質。

目前看來大口徑非球面鏡成形及拋光機台已似乎不再有輸出許可的困擾，參訪時有見到蘇州大學向其訂製之直徑 500 mm 非球面成型機(利用圖 2.2 概念)，雖然機台設計概念與其他較小型機台類似，但該公司也將其具體實踐成形，可見基礎功夫扎得深，一法通萬法通。此外，本次參訪中可明顯看出大陸這二三年來的對外採購精密加工機台能力大幅提升，中心如何持續保持技術優勢，值得注意。

參訪中可見該公司物料管理值得學習，由於該公司均於接受訂貨後才開始生產機台，又由於機台零件有部份共通性，因而該公司必須保持定量之庫存以備不時之需，因此物料管理就顯得相當重要。該公司對於物料管理有些類似物流中心管理模式，倉儲整體外觀明亮整潔，中心機械廠目前也正朝此方向努力。此外產品組裝線現場也相當整齊，維持良好的工作場所與氣氛。

（三）SCHOTT Glass

SCHOTT Glass 為世界知名光學玻璃材料製造廠，公司創立已百年，目前為歐洲光學玻璃製造中心，世界上有 80 個分廠，總員工數達 16,000 人，產品範圍含光學毛胚、液晶電視面板、高溫廚具玻璃、藝術玻璃及醫學用玻璃等。本次參訪為總廠，主要生產玻璃毛胚及平面濾光鏡，廠內除熔鑄機台外，還有成型機及平面拋光機。Schott 的玻璃毛胚主要分成三部份：(1)一般玻璃，(2)濾光玻璃及(3)零膨脹玻璃(Zerodur)，目前以濾光玻璃量最大。

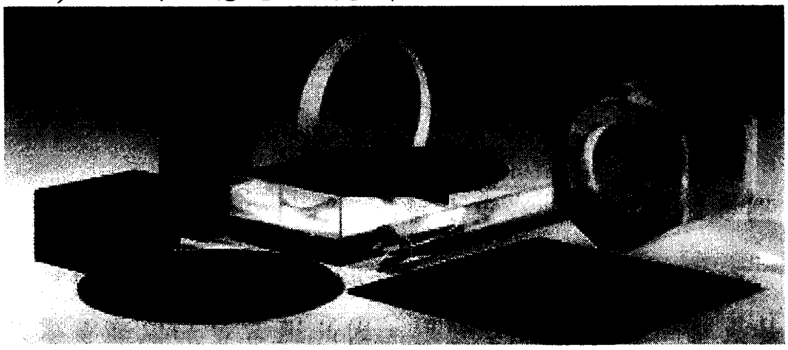


圖 3.1　Scott 公司玻璃及其應用

本中心目前正進行 30 公分口徑遙測模組開發計畫，其中主次鏡所選用材料為 Zerodur，本次參訪主要乃就此材料之性質及製造流程進行瞭解，並與原廠技師討論未來開發計畫選用光學元件材料必須注意事項。

表 3.1　Zerodur 熱膨脹等級

	熱膨脹係數
Expansion class 2	$0 \pm 0.10*10^{-6}$ K^{-1}
Expansion class 1	$0 \pm 0.05*10^{-6}$ K^{-1}
Expansion class 0	$0 \pm 0.02*10^{-6}$ K^{-1}

Zerodur 為一陶磁玻璃材料，其熱膨脹係數極低，主要用於溫度變化大且變形量要求低者，例如太空儀器及半導體

製程中晶圓承載及定位。依熱膨脹係數，Zerodur 可分為三等級，如表 3.1 所示。

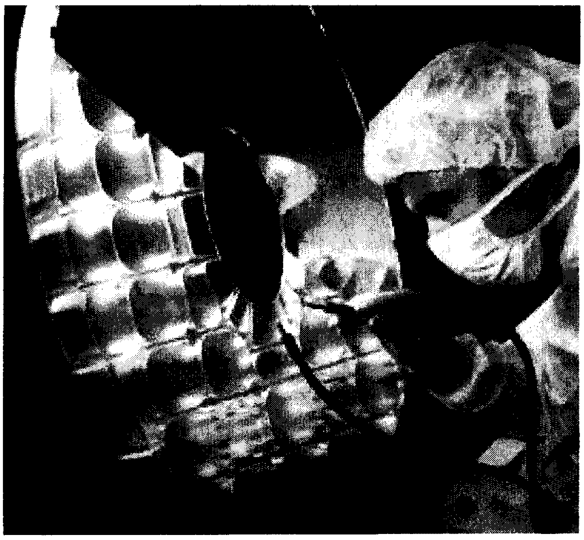


圖 3.2　Zerodur 減重主鏡

Zerodur 材料性質如表 3.2 所示，整片毛胚應用於主鏡其重量太重，易引起自重變形，因此通常會加以減重處理，如圖 3.2。減重處理時以專用刀具在光學面背後直接加工成型至所需樣式，通常減重比可至 65%，減重完畢後之鏡片會加一酸洗去應力手續，確保鏡片穩定性。

表 3.2　Zerodur 材料性質

Density	2.53 g/cm^3
Thermal conductivity at 20°C	1.46 W/(m*K)
Thermal diffusivity at 20°C	$0.72*10^{-6}$ m^2/s
Thermal capacity	0.8 J/(g*K)
Young's modulus at 20°C	90.3 Gpa
Poisson's ratio	0.243
Knoop hardness 0.1/20	620

依氣泡、脈紋及雙折射現象，Zerodur 也分成數等級，各等級之數值如表 3.3 所示，若要求太空等級，class 111 可

符合需求。

表 3.2　Zerodur 等級分類

	standard	special	Class 3	Class 2	Class 1	Class 0
projection of all inclusions in mm^2/ volume of 100 cm^3	2.0	1.0	0.5	0.25	0.1	0.03
average number of inclusions/100 cm^3	5.0	5.0	4.0	3.0	2.0	1.0
Maximum diameter of individual inclusions in mm for different diameters or diagonals of the ZERODUR part						
in the critical volume						
< 500 mm	1.4	1.2	1.0	0.8	0.6	0.4
< 2000 mm	2.0	1.8	1.6	1.5	1.2	1.0
< 4000 mm	3.0	2.5	2.0	1.8	1.6	1.5
in the uncritical volume						
< 500 mm	3.0	2.0	1.5	1.0	0.8	0.6
< 2000 mm	6.0	5.0	4.0	.0	3.0	3.0
< 4000 mm	10.0	8.0	6.0	6.0	6.0	6.0
Stress birefringence caused by (nm/stria) for parts with diameters or diagonals						
< 500 mm	60	45	30	5		
< 2000 mm	60	45	30*	30*	5*	
< 4000 mm	60	45	30*	30*	5*	
* only applies to the critical volume in the area of the operating surface. All others as with special quality.						

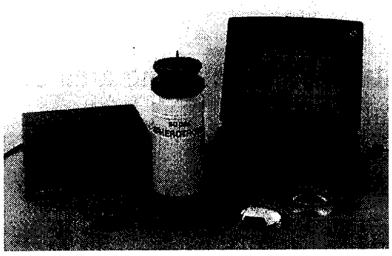
玻璃製作過程中，回火為最難控制步驟，2m 直徑之 Zerodur 鏡片回火過程約需一個月，故需準許多類似貨櫃之冷卻室。此外，加溫熔解前之預備工作也很重要，因為關係玻璃材料純度良否。大於 1m 之大型鑄件熔鑄後表面缺陷通常只要切除 30 mm 的外衣即可取得均勻良質材料。

（四）TRIOPTICS

TRIOPTICS 公司為世界知名光學元件及系統檢測儀器，並且日益茁壯，市場佔有率逐年攀升。中心今年度因為鏡頭組裝需求，向其採購偏位分析儀，此行主要目的在於出廠前訪視儀器狀況並瞭解該公司儀器發展最新動態。

該公司與各項生產的檢測儀器，該公司商品化產品主要分成四大項，

1. OptiTest：有 OptiSpheric、OptiCentric 與 OptiAngle 等量測儀器，涵蓋偏心誤差、有效焦長、曲率半徑、角度或平行度和 MTF 等等的量測，本中心所採購儀器即屬這項類。
2. Prism Master：專門設計來量測稜鏡角度的儀器，依其量測方式可分為絕對(absolute)與比對(comparison line)量測兩種。
3. Spherometer(球徑計)：為一種方便快速量測曲率半徑的儀器，精度高且較不受操作者個別因素影響。本中心光學早已在數年前就使用該產品。



4. Autocollimator(自準直儀)：為其大部儀器的最基本配備，可分成目視與電子式兩大類，其用途非常廣泛，準直校正的各種檢測都可以運用的上，如組裝定位、平坦度(如圖 4.2)或垂直度檢驗等等。

除此之外，該公司也與其它公司、研究機構或德國政府共同

出資開發未來儀器所需之原型機台。

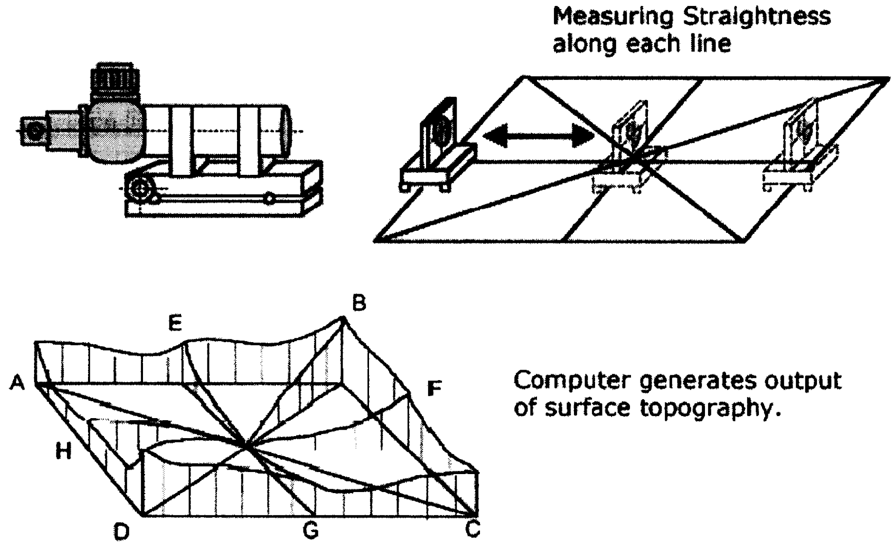


圖 4.2 平面平坦度量測概念

以下就該公司一些儀器之功能及原理概念簡述如下：

1. 鏡片或系統組裝對心調校與檢測

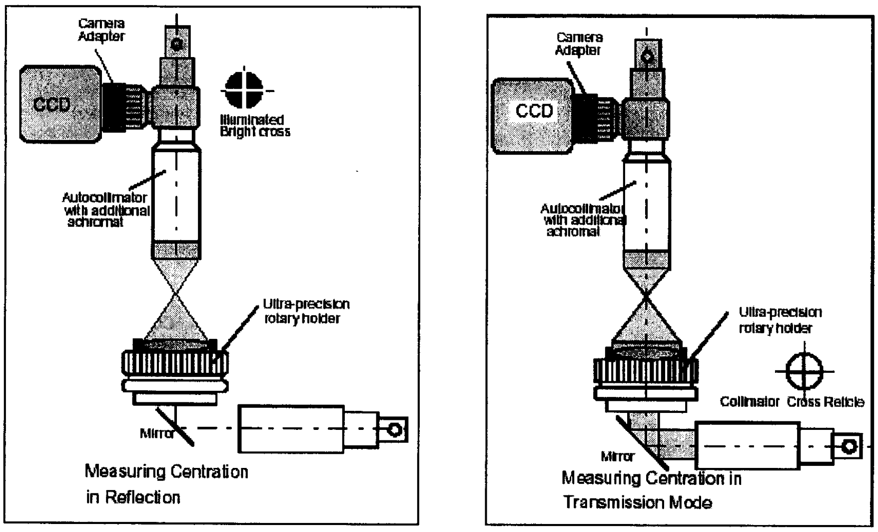


圖 4.3 鏡頭組裝量測概念

對心誤差檢測依其工作原理大致可分成穿透(Transmission)與反射(Reflection)兩種方式，可由下圖示來說

明，由準直儀(Transmission mode)或是自準直儀本身(Reflection mode)發出的十字標靶經由鏡片透射或反射進入自準直儀內的 CCD 或目鏡，當鏡片或鏡組本身有偏心誤差存在時，隨著旋轉平台的轉動，由 CCD 所觀察到的十字標也會繞出圓形的軌跡，此圓形軌跡的半徑其代表偏心量的大小，半徑愈大，偏心誤差就愈大。

2. 曲率半徑量測

曲率半徑的量測除了自準直儀外，還需要一光學尺做位置的紀錄。其原理是由自準直儀發出的十字標靶可由鏡片頂點表面(cat's eye position)以及鏡片曲率中心處(center of curvature)反射回到自準直儀並成像在 CCD 上，藉由光學尺紀錄兩個位置的差，可以求得鏡片的曲率半徑大小，如下圖所示。

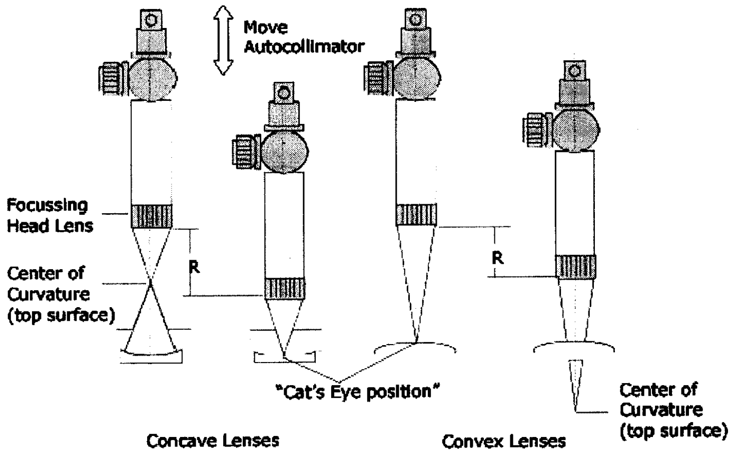


圖 4.4 曲率半徑量測

3. 有效焦長(Effective Focal Length)

有效焦長的量測需要一已知寬度的雙狹縫標靶，由準直儀發出的光經過雙狹縫後，打在待測的光學元件或組件上，經過一 Relay lens(或 headlens)後，進入自準直儀內成像在 CCD 上，其詳細光路可由圖 4.5 中得知。

計算成像在 CCD 上的雙狹縫寬度，與原雙狹縫寬度相比可得到其放大倍率，進一步利用自準直儀與 relay lens 的焦距長求得待測件的有效焦長，其關係如圖 4.6，

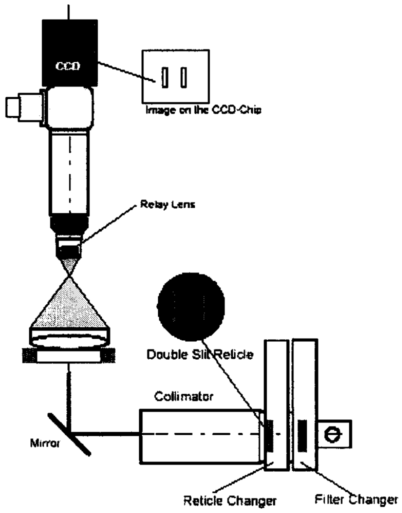
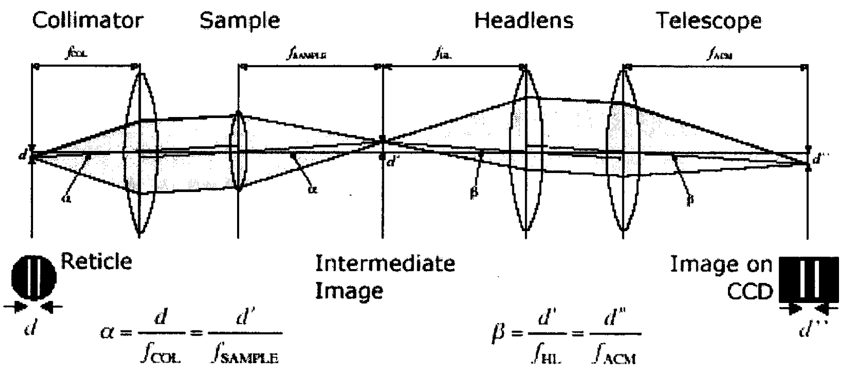


圖 4.5 有效焦長量測概念



$$
\begin{aligned}
f_{SAMPLE} &= \frac{d'}{d} f_{COL} \\
&= \frac{d''}{d} \frac{f_{HL} f_{COL}}{f_{ACM}}
\end{aligned}
$$

圖 4.6 有效焦長計算概念

4. 背焦長(Back Focal Length)

紀錄上述有效焦長的位置，再利用自準直儀找到鏡片表

面頂點的位置(cat's eye position)，由上兩位置的差可以計算得鏡片的背焦長度。

5. 楔形角度量測(Wedge measurement)

楔形角度的量測乃利用上下兩表面分別反射由自準直儀來的十字絲光線，計算兩光點在 CCD 成像面的距離，可以求得此楔形角度的值，也常用來檢測光學平板的平行度。詳細光路安排與關係式可由下圖表示，

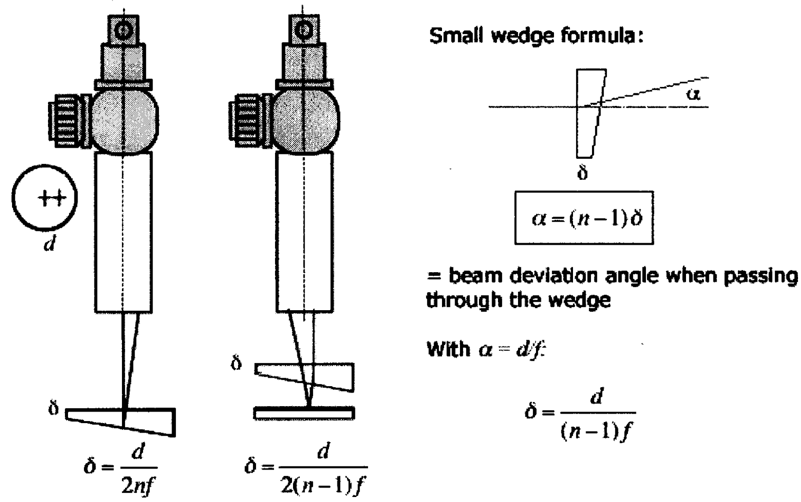


圖 4.7 楔形角度計算概念

利用此楔形角度量測方式，也可用來驗證本套儀器的量測精度，本次所購買的附件中，有一已知角度的標準楔形平板，其角度是由德國 PTB (Physikalisch-Technische Bundesanstalt)所校正，可用來驗證自準直儀量測的準確度與解析度，並且具國際量測追溯性。

6. 旋轉擺動量測(Wobble Measurement)

由待測表面反射回自準直儀的光點或十字標靶，當待測件旋轉時，可觀察其在 CCD 上的軌跡，即是其旋轉擺動誤差。旋轉平台的精度會嚴重影響待測結果，因此需特別考量，中心所採購的設備其旋轉平台是採 air bearing 的高精度

旋轉平台。

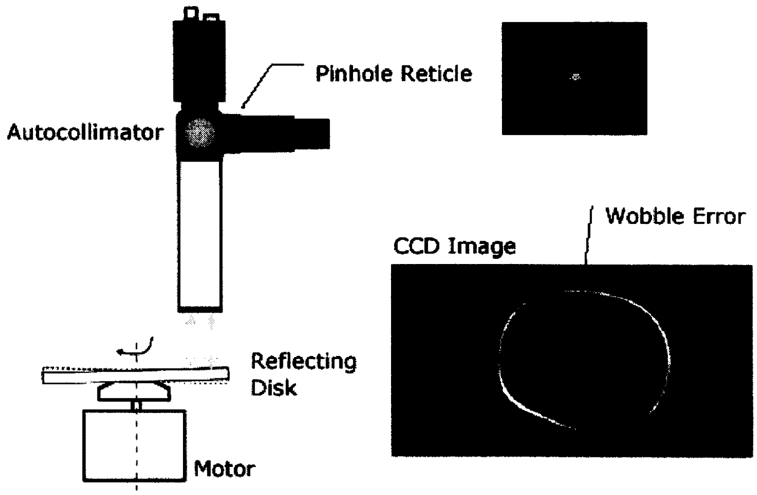
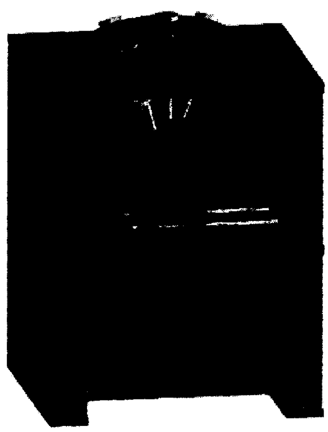


圖 4.8 擺動誤差計算概念

除此之外，近年來也針對客戶的個別需求開發新的檢測儀器，例如 MTF 檢測儀(如右圖)，與一般 MTF 量測儀器不同處是，這套儀器專為手機數位相機鏡頭檢測之用，有特別的鏡頭夾持載台，同時有五個 sensors 在不同角度(含軸上 On-axis)的 MTF 量測，因此可以迅速得到五個角度的 MTF 值量測結果，兼具線上大量檢測的優勢，圖 4.10 為其量測的結果畫面。



另一針對客戶需求所設計，在原有對心量測設備上搭配自動點膠機、壓電片致動調整裝置與 UV 燈所組成的自動對心點膠機台，為一自動化鏡片與鏡筒組裝灌膠的設備，非常適合高精度且須大量生產的需求，值得我們學習並改進現有組裝調校程序。

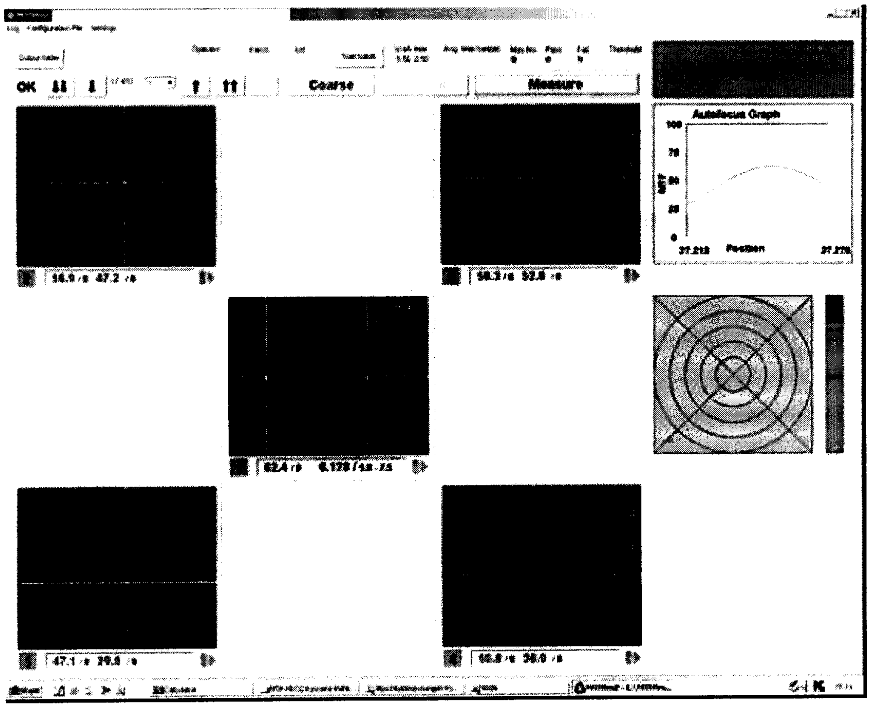


圖 4.10 手機數位相機鏡頭 MTF 量測畫面

圖 4.11 自動對心點膠機台，對心後灌自動灌膠情形

目前該公司研發兩部儀器，都是用來量測建構待測面表面特性，包含三維外形與表面粗糙度等，其量測原理(如下圖)是利用待測面表面對入射光反射後波前形狀誤差的改變來

獲得待測面表面傾斜度(斜率)，經由積分運算得到表面的形狀，可稱為一種波前量測儀。

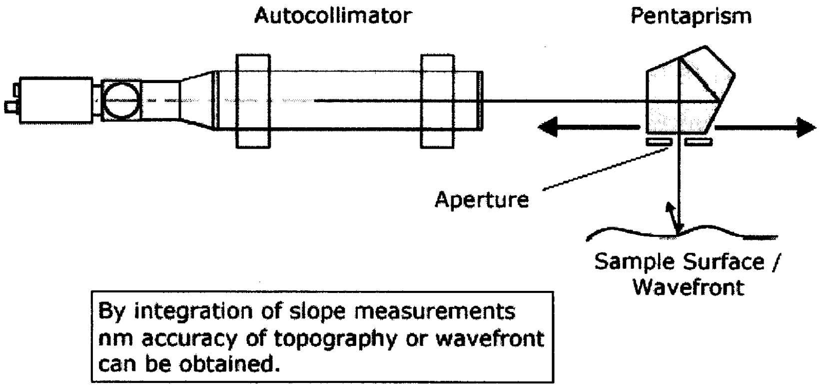


圖 4.12 波前量測概念

另一項研發的儀器(Deflectometry)則是一項合作的研發案，主要用來量測矽晶片的表面平坦度，目前是以 12 吋為目標，與一般 3-D profiler 最大的不同是，它的量測時間相對短很多，只需將矽晶片旋轉一圈就可完成掃描，其原型機內部構造如下圖示，使用一遠心鏡頭為觀測鏡頭。

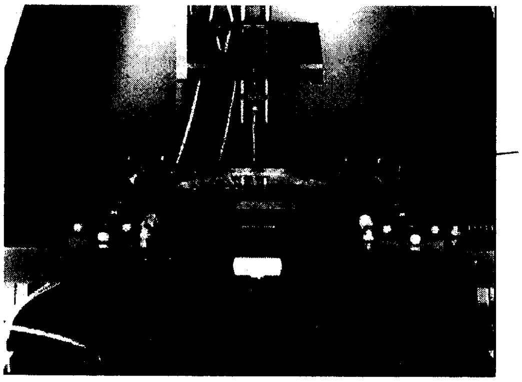


圖 4.13 矽晶片的表面平坦度量測儀

Trioptics 目前員工約只有二十多位，負責產品前段的研發設計與後段的組裝與調校，至於光機元件的製造生產則完全交由其協力廠商，因此其工作環境顯得簡單而整齊，人員少卻能發揮最高經濟效益，從簡單的原理充分運用發展出多

樣的檢測儀器，值得我們深思與學習。

觀看 TRIOPTICS 的產品，大多應用都源自準直儀及自準儀，先將此部份基礎打穩之後，後續應用即可配合基礎技術輔以角度旋轉與直線平移機構及 PC 化控制即可組成無數相當有使用親和力但很實用之量測儀器。在此可看出，這些儀器背後的光學原理並不複雜，因此該公司發展重心及主力均用於機構設計及軟體撰寫，此點與 LOH 及 OptoTech 類似。

此外該公司的儀器結合現在非常流行的 PC 介面，使得軟體撰寫的靈活度增加，並且未來若發現相同有更多應用，只要使用軟體更新即可；對於檢測報表的輸出，也可結合當時流行的應用軟體搭配，使用相當方便。

此次考查也有幸得與公司負責人 Mr. Eugen Dumitrescu 對話，其中也討論到他如何在這麼多的題目中決定公司營運方向? Mr. Dumitrescu 回答相當簡明：直覺。這也讓人連想到 Mr. Dumitrescu 對其工作是相當投入的，心思無時不在思考公司儀器的發展，甚至對於商展中各類情報的搜集也有獨到工夫，才能有如此簡截的回答。

（五）Moeller-Wedel Optical

Moeller-Wedel Optical 創立約一百五十年，主要製作光學檢測所需之高精度準直儀、自準儀、角度儀、干涉儀等，目前屬於 HS 集團下之一支。TRIOPTICS 公司就是一些該公司離職人員所創立。

準直儀及自準儀的搭配可以量測光學性質或進行光學調校，如系統焦長、稜鏡角度、光軸對準等，角度儀基本上就是搭配角度量取設備所做成。系統焦長量測原理如圖 5.1 所示，自準儀提供一已校對距離之 reticle y'，由自準儀將光線聚集後讀取 reticle 中距離值 y，待測系統焦長即為 $f' = f_k \cdot y'/y$。準直儀及自準儀標準產品焦長由 90 mm ~ 1100 mm，也有焦長 2000 mm 口徑 250 mm 之準直儀。準直儀及自準儀內中所放置之 reticle 玻璃由協力廠商完成，協力廠商資料如下：

POG Präzisionsoptik Gera GmbH
Gewerbepark Keplerstr. 35
D – 64734 Gera
TEL: +49 6163 912130
FAX: +49 6163 912132
www.precisionsoptic.com
praezisionsoptik@t-online.de

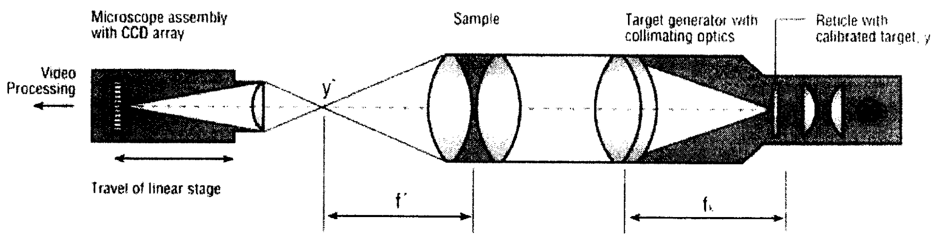


圖 5.1 Moeller-Wedel Optical 系統焦長量測原理

有關變焦鏡頭之測試，該公司也準備了一套專用量測設備，當鏡頭變焦後，可以上述方式量測焦平面變化量，此變化量即為一般相機生產廠商所在意之品管參數。

儀器使用介面方面該公司與 TRIOPTICS 使用 PC 及影像擷取卡概念不同，走的是專用控制器的路，主要考量在於輕量、可移動、現場操作，此外若影像擷取卡或 PC 做業系統更換，無需擔心維護問題。此專用控制器由合作廠商 Schnabel 負責開發，軟體也由此公司負責，控制器可與 PC 接線，圖 5.2 為該公司 ELCOMAT 電子式自準儀使用情形，可見專用控制器。

近年來由於 TRIOPTICS 的加入競爭，加上光纖對位需求，公司整體營運逐漸調整專注於高精度角度儀發展，最高精度可達 0.005 弧秒 (25 nrad)，一般精度為 0.1 弧秒 (0.5 μrad)。

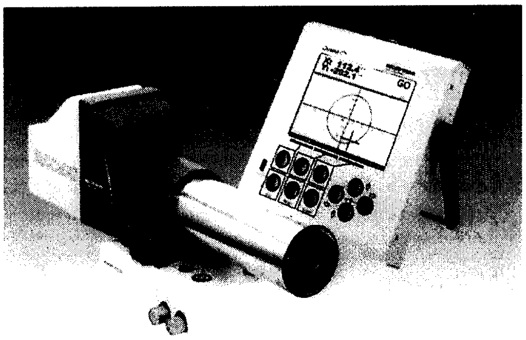


圖 5.2　電子式自準儀

干涉儀方面，該公司也有 4”及 6”干涉儀及小型干涉儀，如圖 5.3。4”及 6”干涉儀標準平面精度可為λ/20 與λ/50 p-v 間，標準球面為λ/10。

該公司有一溫度控制之實驗室可做為角度校對標準用，該標準回溯至德國 PTB，系統焦長部份則回溯至英國 NPL，可稱為二級標準，有關於不確定度的計算，該公司也

不甚清楚。

中心先前也向該公司購置一角度儀，量測稜鏡角度，當至中心售後服務時發現該機台心操作人員身高不同產生的操作不便後，回國後即立即改善該機台的設計，增加一調整高度的機構，展現該公司產品改善機動性。

該公司之物料管理也相當完善，元件均有個別的抽屜儲放，需要時再取出。機械及光學元件並不在組裝地點製造，委由集團分公司及協力廠商完成，因此工作環境維持相當好。

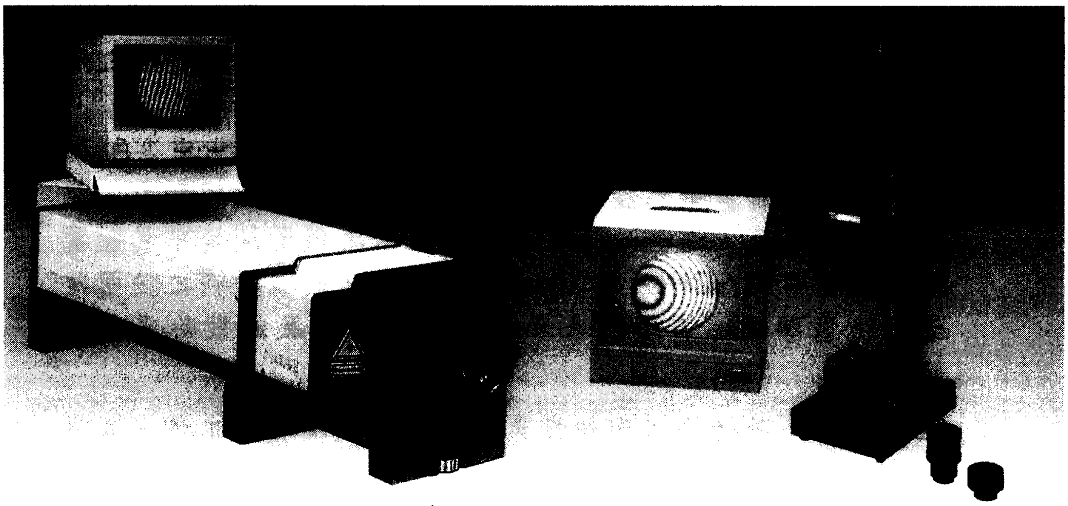


圖 5.3　4"干涉儀及小型干涉儀

四、達成任務

此次赴歐考察考察精密儀器工程技術，針對本中心未來計畫發展所需之非球面製造檢測、光學元件製做檢測及國家標準實驗室建立等項目之發展現況進行瞭解，以利計畫之推行及後續計畫規劃。藉由拜訪這些廠商，實地瞭解該機構執行推動工作情形，更能掌握其技術能量與發展趨勢，透過彼此拜訪溝通，更有利雙方技術交流。茲將此次考察所達成任務，概述如下：

(一) 瞭解國際著名光學檢測、光機儀器製作廠商之最新產品與技術現況，充實本中心在光電遙測技術整體發展之有關資訊。

經由考察 TRIOPTICS 及 Moeller-Wedel Optical 等檢測公司，體會許多儀器發展重要項目，如使用介面親和力、儀器整體完成度，這些心得將逐漸於未來之儀器開發中具體實踐。經由考察 SCHOTT Glass 瞭解太空級玻璃材料之使用及選用注意事項，有助於未來承接酬載設計及組裝計畫之執行。

(二) 督導「偏位分析與組裝系統」檢測設備驗收工作，並就相關議題做研討，期能進立起中心精密光機組裝定位分析之技術。

利用此次考察機會實地瞭解該機台應用於本中心鏡頭之組裝，並從中得知中心光學鏡頭設計所欠缺考量點，有利於未來光學設計之改善。

(三) 觀摩精密光電儀器製作、鏡片檢測技術，強化與國外研究機構之技術交流與溝通管道。

經由此次考察瞭解最新非球面機台之功能、概念及發展現況，增加未來計畫方向及預算執行規劃之基礎知識，使規劃符合世界潮流。

本次也利用考察機會當面邀請各公司專業人員協同中心人員在台開設訓練班，均獲得正面回應。

(四) 考察相關廠商對於實驗室品質管理的方法、儀器設備管理維護與技術評估等，以做為未來實驗室申請認證做準備。

本中心規劃明年度開始建立光學元件檢校實驗室，利用此次考察機會瞭解各廠商校對標準回溯情形，有助於未來中心標準檢校實驗室之建立。

五、心得與建議

一、LOH Optical Machinery，SCHOTT Glass 及 Moeller-Wedel Optical 公司均有上百年歷史，這些年所建立起來者為一令人信賴的口碑，見到這些廠牌即表示品質的保證，可見日久即有功，品牌的建立非一朝一夕可幾。而這些公司在長時間時代競爭仍能屹立不搖，除口碑外，尚需不段的創新，符合時代潮流，甚至領導潮流。中心在國內而言為光學界的先驅，也建立一些口碑，近幾年來致力於非球面鏡製造及檢測使得中心成績更加輝煌，未來仍需思考如何維持。

二、OptoTech 及 TRIOPTICS 與上述公司相較雖屬市場新兵，但仍能在老廠的壓力下展現出傲人成績，甚至有時還超越老廠，實有賴機動及靈活之機台設計及親切人機界面。可見新公司若能建立獨特特色，雖無品牌優勢仍能逆勢向上。

三、可以預見中心未來預算爭取將更困難，逐年添購加工機台心願將不見得能如預期順利。中心也許可以開始考慮將中心長年之粗細磨及拋光經驗與工作母機廠商合作，先由小機台開始建立雙方合作機制及默契，開發出適合的加工機台。倘若未來大口徑鏡片加工設備受限無法由國外取得，中心還有機會取得工作機台機會，甚至在小鏡片加工機台尚未取得前即由雙方合作開發完成也未可知。

四、從參訪中也可感覺出，這些廠商將大部份心力放置於機台機構設計加工及控制軟體撰寫上，整體機台完成度相當高，甚至有時無法挑剔。中心設計儀器普遍欠缺一整體包裝，令人覺得完成度較低，未來中心應可在現有基礎上朝此方面努力。

五、 私人公司將本求利，因此物料管理方面相當值得我們學習，有些公司會保持定量之庫存以備不時之需，有些公司則採元件外包方式，二者經營雖略有不同，但廠區整體外觀明亮整潔，此外產品組裝線現場也相當整齊，可維持良好的工作場所與氣氛。

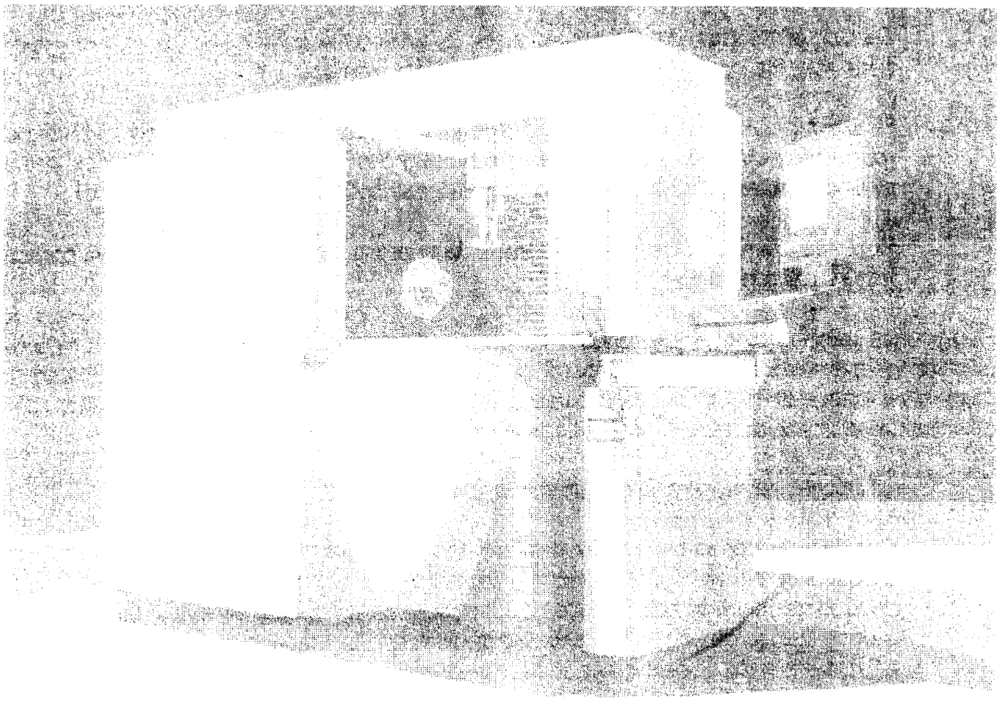
六、 Trioptics 目前員工約只有二十多位，負責產品前段的研發設計與後段的組裝與調校，至於光機元件的製造生產則完全交由其協力廠商，因此其工作環境顯得簡單而整齊，人員少卻能發揮最高經濟效益，從簡單的原理充分運用發展出多樣的檢測儀器，值得我們深思與學習。

七、 各廠商中可見老經驗的技術人員，這些技術人員不但相當瞭解專業領域技術，不但能協助公司解決問題，尚能在實際工作中將經驗傳承下來，中心光學廠目前即有此特質。因此培養高級技術人員，加重強調完成工作的能力，而非僅是強調學歷應是我們可以思考的方向。

附錄 廠商資料

OptoTech Concept for the Production of Aspherics

Grinding, Polishing, Correction



Basic Concept

The OptoTech generating and machine concept for the production of aspherics mainly aims at optimizing two aspects:

- Avoidance of high-frequency surface aberrations which can only be inadequately eliminated by subsequent corrective polishing, and which considerably reduce the optical quality of the surface due to resulting tangent errors

- Considerable shortening of the process time in order to make the use of ashperics more economical

The whole process consists of three interlinked steps:

- Grinding of the lens, leaving enough stock for subsequent polishing of the contour, which is done when the lens is finished with the large-surface area tool

- Finishing (polishing) of the lens with a large-surface area, flexible polishing tool consisting of a granite body which has the inverse aspheric form or best fit radius, and a flexible foam pad of a suitable thickness which is glued onto the granite tool body and holds the polishing foil.

- Final measurement of the lens with a tactile, form testing instrument and topographic correction with a small contact area tool.

Large-area polishing considerably reduces the process time on the one hand, but it also produces a very long-wave residual aberration. Depending on the specific lens geometry, this residual aberration lies within a range of PV 1 to 2.5 µm. If a greater accuracy is required, this long-wave aberration can be compensated for in a subsequent correction process.

The overall process sequence is divided up into two areas:

- One-time process steps, e.g. for determination of the polishing stock removal by the large-surface area tool and the stock removal capacity of the topographic tool. These steps have to be performed once for each surface type. If process variables, such as, e.g., the diameter of the grinding tool, consistency of the polishing medium, and tool capacity are changed later, certain adjustments in the process may also have to be made.

- Recurring process steps, such as grinding, finishing, and correction of the surface. These steps have to be performed for each lens which is to be produced.

Let's now talk about the individual process steps – from the setup of the generating machine to corrective polishing with the topographic tool. The scaling in the contour images has been set to the expected aberration and therefore only shows the trend, and not an absolute deviation. For details about how to operate the machine in order to perform the steps described here, please refer to the relevant documentation.

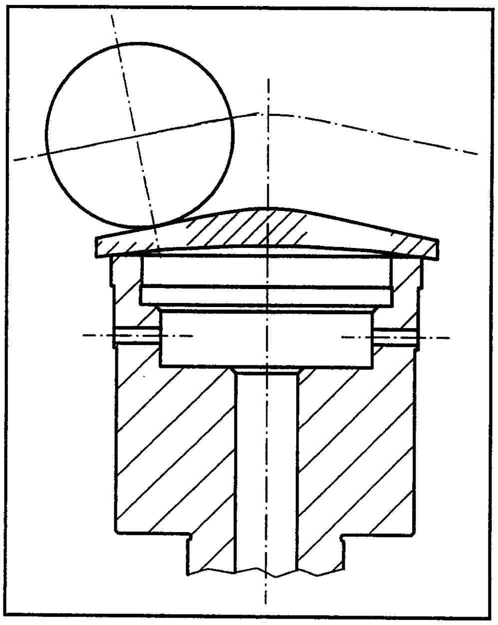
<u>1. One-Time Process Steps</u>

1.1 Setup of the Generating Machine

When producing an ashpere with a grinding wheel, two parameters in particular affect the accuracy of the geometry:

- Position of the end point in the CNC file relative to the axis of rotation of the workpiece (lens). Generation of the surface generally takes place from the edge to the center of the lens, the end point of the tool thus lies in the center of the lens surface on the axis of rotation of the tool spindle. This end point must be reached with extreme accuracy, in fact, even more accurately than can be guaranteed by basic adjustment of the machine, because the position also depends on the mechanical load which prevails during the production process, or, roughly speaking, on the size of the lens.

- Diameter of the grinding wheel; if this deviates from the diameter which was used as the basis for calculation of the CNC file, a radius error occurs, either in the convex or in the concave, depending on the direction of the deviation.



Grinding of aspheric with a wheel-tool

These two variables must therefore be set first on the generator to meet the specific requirements for the lens which is to be produced. It should be noted here, that the two variables are interdependent in as much as a shift in the end point also causes a radius error.

1.1.1 Correction of the Contour End Point

Correction of the contour end point relative to the axis of rotation of the lens should be done before the the radius of the tool is corrected, because this type of maladjustment also feigns a tool diameter error. To achieve as uniform a stock removal as possible for the lapping tool, adjustment of the X-axis should be done for the rough grinding spindle and the lapping spindle.
To determine the direction in which the X-axis needs to be corrected, the desired asphere is generated with the tool spindle which is to be adjusted, the result is then measured on a form testing instrument, and the surface deviation with the given asphere parameters and the best fit vertex radius is shown.
If the axis is maladjusted, the contour deviation will have two possible different appearances, as follows:

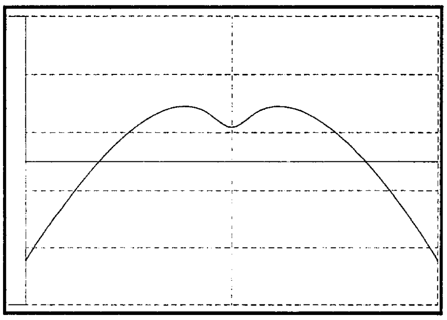
Convex Aspheres

Contour deviation in **M**-form: The tool did not reach the center of the lens
Contour deviation in **W**-form: The tool overran the center of the lens

Concave Aspheres

Contour deviation in **W**-form: The tool did not reach the center of the lens
Contour deviation in **M**-form: The tool overran the center of the lens

Depending on which spindle was used (i.e. whether the contour was followed from left to right, or from right to left) and on whether the tool or the lens is moved when the X-axis is moved, an adjustment of the X-axis must now be input at the controller in the appropriate input field of the OptoTech user interface for the tool spindle in question.
For correction of, e.g., an M-form on a convex lens generated on an SM 100 with the left spindle (generation from left to right), and movement of the tool with the X-axis, correction must be done in the +x-direction (i.e. the tool must be moved closer to the center of the lens, because the tool didn't reach the center). The drawings explain these as a case of principle.



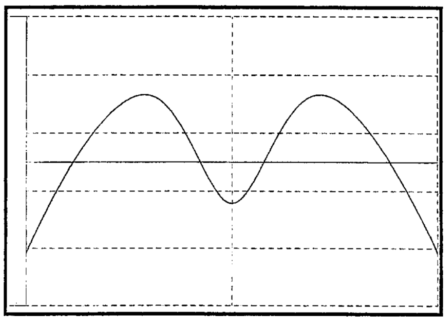


Fig. 1: Measuring results after grinding with maladjusted end point *Fig. 2: Result after adjusting the radius, M-structure*

There is no general rule about how much correction is needed for complete compensation of the error, because the amount depends on the shape of the asphere and on the tool geometry. The final

adjustment should be made in steps of approx. 5µm and then a surface should be generated again. Any overcompensation is easy to detect, because the error image will change from M to W or vice-versa.
A W-form should be avoided on the test lens at all costs, because this is generally carried on throughout the whole production process and is much more difficult to correct later than an M-structure.
An axis which has been adjusted in the way described will not be completely changed for another lens; if, however, the test lenses differ considerably in size, specific, individual setting may be necessary.

1.1.2 Correction of the Tool Diameter

The adjustment described in 1.1.1 exerted influence on the radius error of the generated surface. If there is still a radius error superimposed on the asphere after the x-adjustment has been made, the tool diameter has to be corrected.
To do this, a surface is generated with the parameters specified in the drawing and the actual vertex radius is determined by adjusting the radius in the software of the measuring instrument accordingly. Here again, the radius adjustment depends on the surface shape.

Convex Aspheres

If the radius is smaller than the desired radius, increase the tool diameter in the input field
If the radius is greater than the desired radius, decrease the tool diameter in the input field.

Concave Aspheres

If the radius is smaller than the desired radius, decrease the tool diameter in the input field
If the radius is greater than the desired radius, increase the tool diameter in the input field.

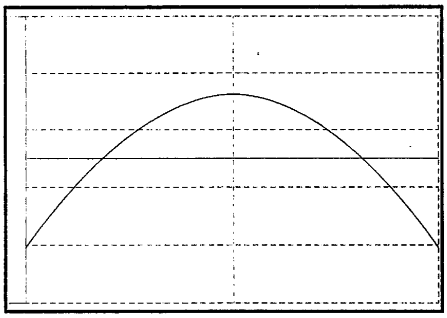


Fig. 3:Concave radius greater than the desired radius

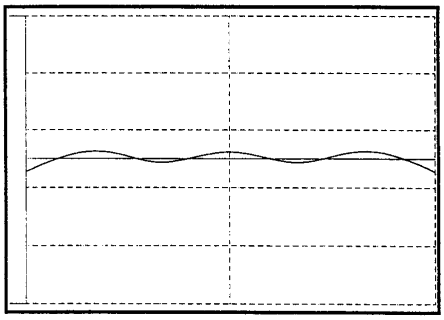


Fig. 4: Best fit radius; difference = radius correction

The tool radius has to be corrected by exactly the amount by which the actual radius of the asphere differs from the desired asphere. A new CNC file must be created with the new diameter value and the asphere must then be reground and measured in order to check that the new diameter is correct.
In the course of production too, the tool diameter must be checked and readjusted in the same way, i.e. by grinding a desired asphere. However, this should be done on a surface which is not actually a part of the production process, because a corrected CNC file will be used in the production run, which may already provide for a radius error in the contour.

This concludes the setup of the generating machine. You can now go on to produce the tool or generate the tool surface for polishing with the surface tool.

1.2 Grinding the Surface Polishing Tool

A suitable tool must be produced for polishing the asphere. This tool generally consists of a granite body which has been ground to the required shape.
In most cases, the tool will be spherical. In some cases, however, it may be better for the polishing performance at the edge to create the inverse of the asphere of the lens (reversal of the preceding sign of the radius and the aspheric parameters) on the tool.
When choosing the contour of the tool, the thickness of the foam pad and of the polishing foil must be taken into account (e.g. 4mm foam + 0.81mm polishing foil = 4.81mm). The effective radius of the polishing tool when it comes into contact with the asphere is most important, because the tool has to deform by at least the amount by which the asphere deviates from the spherical form.
The thickness and firmness of the foam depend on how much the asphere deviates from the spherical form.

So, the spheres for the granite tool body have to be generated taking the following into consideration:

Convex Aspheres (concave tool)

Absolute tool radius = best-fit of the asphere + thickness of the compressed polishing foil

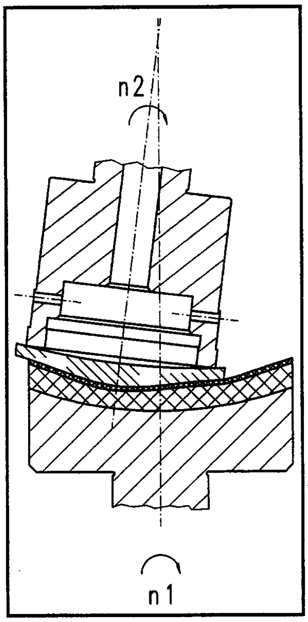
Concave Asphere (convex tool)

Absolute tool radius = best-fit of the asphere – thickness of the compressed polishing foil

The outside diameter of the granite tool body should not be less than 90% of the diameter of the asphere in size.
After the tool body has been ground, the foam pad and the polishing foil must be glued into place and must then be left to stand long enough for glue to fully harden.

1.3 Determination of the Polishing Parameters for Large-Area Polishing

The ideal process parameters for the polishing operation must now be found for the large-surface area polishing tool.
To do this, you have to generate a lens on the machine which has been set up in the way described in 1.1.
Next, the polishing tool and the lens are inserted into machine and are clamped. It has proven advantageous to put the concave components (i.e. the lens, if the tool is convex, or vice-versa) on the bottom spindle. This ensures that enough polishing medium collects in the middle area of the lens, which is particularly beneficial for large lenses.



Polishing of aspherics with large tool

The contact pressure of the tool is controlled by entry of the length, whereby an input value of the actual tool length minus x causes a compression by the amount of x. The compression should normally be in the range of the amount by which the asphere deviates from the best fit sphere. However, the feed must be determined by trial and error based on the polishing results. If noise develops during the process, this is an indication that the contact pressure is too high.
Swivelling of the B-axis should take place symmetrically around the zero position of the best fit radius and the swivel range should be selected so that the tool strokes lightly over the edge of the lens.
Depending on its size, the lens should be polished at this initial setting for approx. 2 min. It must then be inspected to determine how uniform the stock removal was.
If the tool has not touched certain areas of the lens yet (because, for example, the asphericity of the surface is too great), the contact pressure should be increased. If polishing did not take place right up to the edge of the lens, the swivel radius must be changed to compensate that.
The changes which occur each time the parameters are adjusted are determined by polishing with the new parameters for a couple of minutes and then checking the polished surface again. This allows you to determine the most suitable polishing parameters and the required polishing time.

1.4 Determination of the Stock Removal by the Surface Polishing Tool

To calculate the stock allowance to be left on the lens when a batch of lenses is ground, you now have to determine how much stock is to be removed by the surface polishing tool. To do this, the previously used lens is ground over again and is given the ideal contour.
When polishing the lens, we recommend the use of a plastic supporting ring which supports the lens contour tangentially at the edge, and therefore prevents the tool from being relieved too much at the edge area and polishing the edge of the lens too much.
This lens is polished with the large-area tool at the preset parameters for the whole time, and is then checked for overall polishing and is measured with a form testing instrument.
For this type of operation, the form error lies within a range of 6 to 15µm , depending on the lens.
The measuring results are transmitted to the generating machine via the network and the appropriate compensation tool path is calculated with the AspheroTool software.
From now on, all lenses are produced with this program file. This basically creates the negated error function of the polishing process, so that after full-surface polishing has been done, only a very small long-wave residual aberration remains.

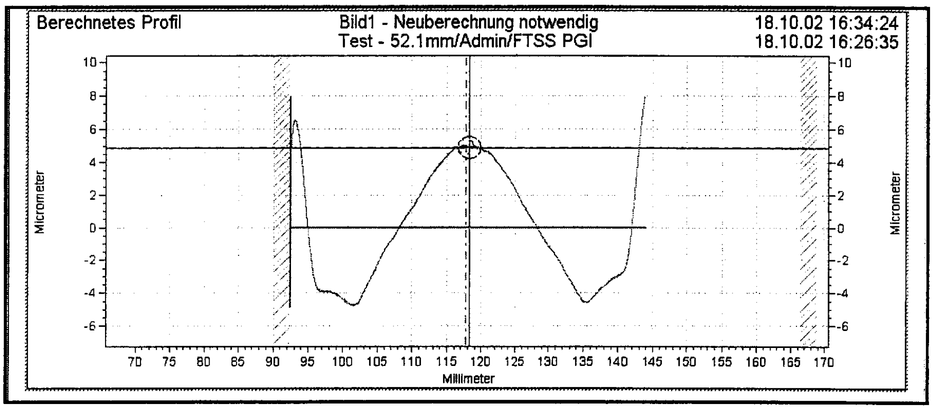


Fig. 5: Polishing by the surface tool

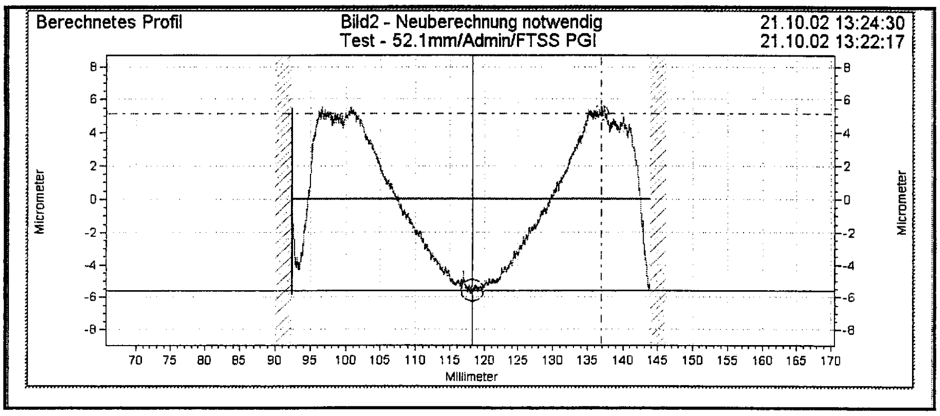


Fig. 6:Inverse error of the grinding contour added

1.5 Determination of the Stock Removal Function of the Correction Tool (Footprint)

The final step of the one-time jobs is to determine the stock removal capacity (footprint) of the correction tool.

To do this, the correction tool is brought into contact with a polished lens surface, ideally a plano-surface made of the same material as the surface which is to be processed, under pressure, at various distances from the center of the surface, with the axis stationary but with the spindles rotating, for a certain length of time. Due to the rotation, a ring-shaped, concentric groove is produced. This is called the footprint and its depth and width for the given machining time are characteristic for the tool used, the contact pressure, and the material.

From two footprints, the correction software can determine the stock removal capacity of the correction tool for every point of the lens, which in turn determines the required dwell time in a certain area of the surface, for later correction of an error function. From that, AspheroTool then calculates the feed function for machining along the surface contour.

Ideally, the plano-surface should have a diameter of 70-100 mm. To determine the machine coordinates which have to be input into the controller for execution of the footprint, you use the AspheroTool software as if you wanted to polish that surface with the correction tool. As the tool length, you select a length which is approx. 0.5 mm shorter than the actual tool length in order to produce a certain amount of contact pressure. However, the lower the contact pressure is, the less precise the footprint will be.

You then generate the job file for the surface and select two positions with the coordinates X; Z; and B from the program listing, whereby one position should be 9 mm away from the center, and the other position should be closer to the edge , but at least 8 mm away from it.

Before you actually create the footprint, the surface must be measured with a digital interferometer and the measurement saved as a reference for the next measurement. The angular orientation of the test lens must also be marked. The lateral resolution of the interferometer must be calibrated for the zoom used.

Both sets of 3 coordinates are then entered in the appropriate input field for the footprint on the screen. Select an application time of approx. 15 seconds. Select a suitable speed of rotation of the lens (always the bottom spindle) based on its size, and set the speed of rotation of the tool, in the same direction of rotation, to about 75% of the speed of rotation of the lens spindle.

Please note that the program should be run at 100% feedrate from the start, i.e. the surface should not be approached at a slower speed whereby the machining operation could take place too soon. Also make sure that sufficient polishing medium is supplied at the time the machining operation is performed.

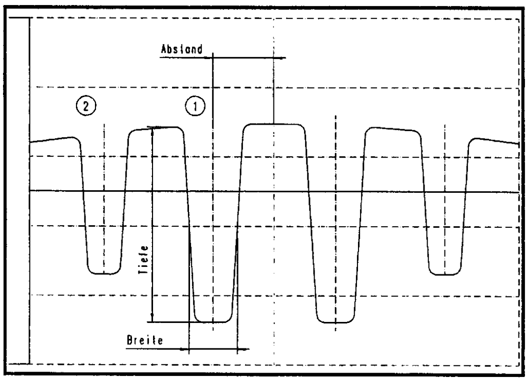


Fig. 7: Footprint Measurement

The depth and width of both footprints are evaluated on the interferometer and the data are entered into AspheroTool. The software now calculates the stock removal characteristics of the tool and is ready for subsequent correction purposes.

2. Production Process Steps

2.1 Grinding and Finishing the Lens

The lenses in the batch are now ground and are then polished and measured with the compensation file generated in 1.4.
Make sure that exactly the same polishing parameters are used as those used for determining the stock removal. This also goes for the consistency of the polishing medium.
Polishing foil wear and the resulting reduction in polishing performance can be compensated for by increasing the running time. If the changes are considerable, step 1.4 may have to be repeated.

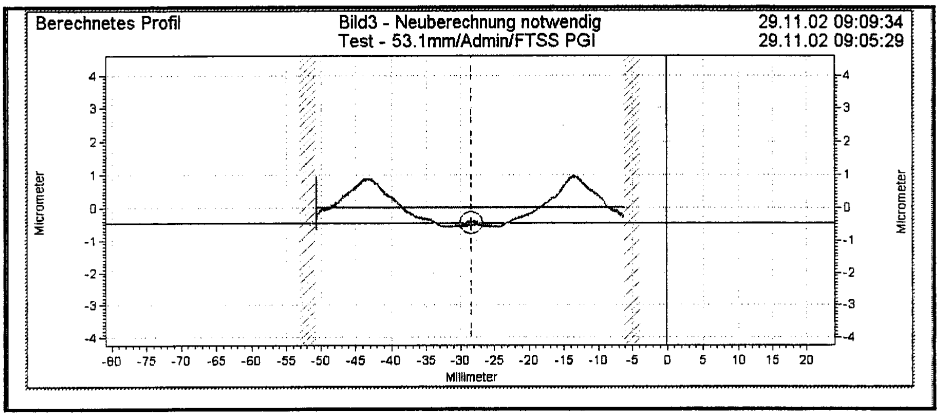
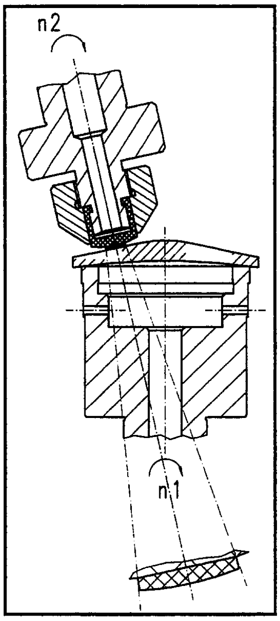


Fig. 8:Residual aberration after finishing

2.2 Corrective Polishing

The measured results for the finished lens are transmitted to the polishing machine via the network and are used by AspheroTool to calculate the feed function for correction of the surface. The surface parameters of the lens and the data for the correction tool are then entered into AspheroTool, the file containing the measuring results is integrated, and the CNC file is then generated.
Every surface will have a different residual aberration and must be measured and corrected indvidually.



Correction polishing with zonal tool

Exactly the same machine parameters must be selected as those used for generation of the footprint. Special effects, e.g. at the edge of the lens or in the center of the lens can be countered with the fine tuning function.
1-2 correction steps are generally needed until the final contour is achieved. To prevent overcompensation of the error, you can use the fine tuning shift function, by intially feigning a higher stock removal capacity of the tool and in this way, slowly nearing the ideal contour. Even though more steps are then needed, no time is lost, because the stock has to be removed from the surface anyway.
The depth of stock removal should always be kept as low as possible to maintain a favourable error/stock removal ratio.

Fig.9 shows a in this way corrected surface. The max. accuracy depends on the surface shape witch is to correct. Best results are reachable with surfaces having the "valleys" all on the same level. So it could be advantageous to accept a larger PV for the pre-polishing, but to have a error shape wich is easy to correct.

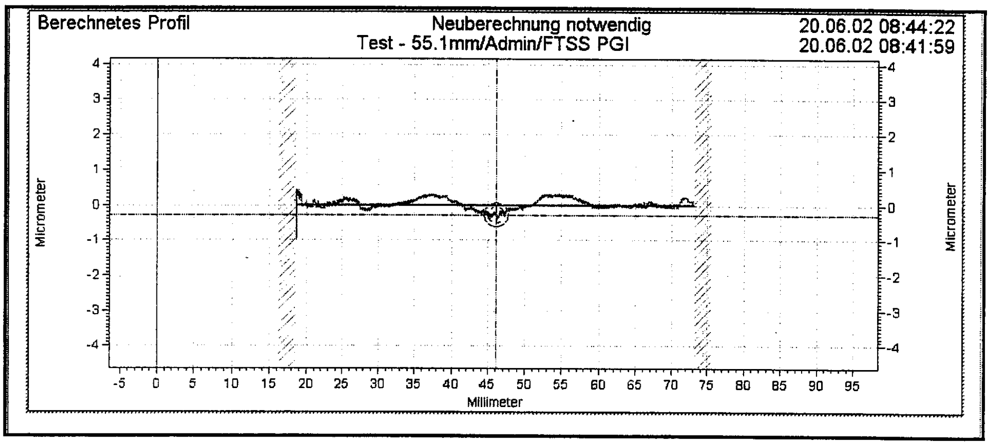
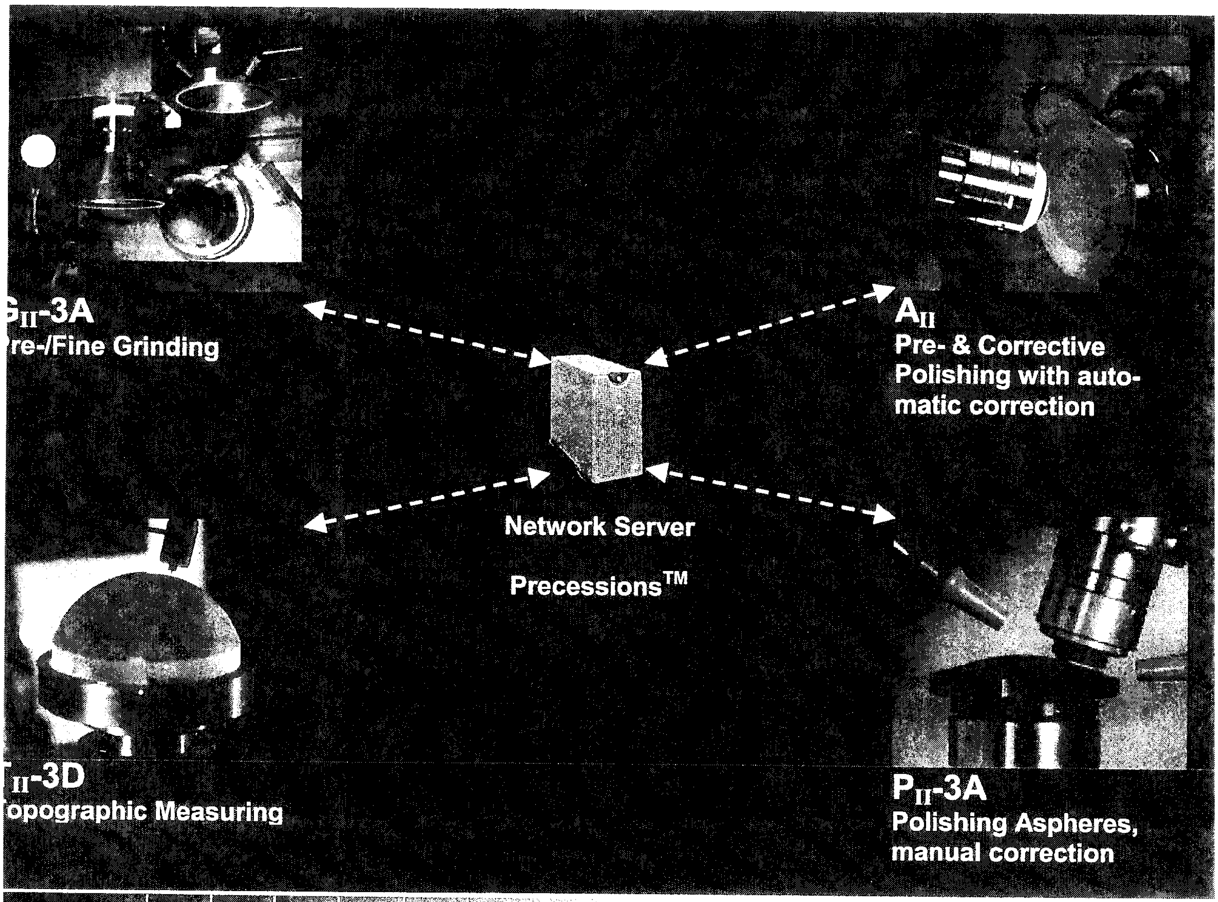


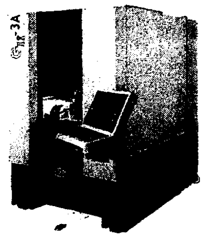
Fig. 9: Surface after the 2 correction cuts

Once a footprint has been taken, you can of course use it to machine a different type of lens to the original one; you simply have to make a factorial adjustment with the Shift function. This allows you to determine and catalog suitable values for various different types of lenses.



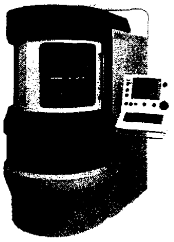
Complete Aspheric Processing

AsphericLine



G_{II}-3A – Pre-/Fine Grinding of Aspheres & Spheres

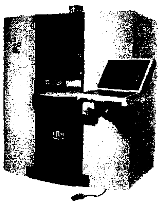
- **Unique processing principles**: cup wheel and disc tool grinding
- **Processes aspheres and spheres**, as well as shaping, chamfering and centering, diameter reduction in one process (job link), Ø 20 to 120 mm
- **Superior** reproducible accuracy
  - Form
  - Surface structure
  - Centering
- **Deterministic, repeatable results** (Gantry design minimizes temp. drift and negative effects of process forces)
- **Unique user interface**, programmed by end user
- **Fully automatic processing** with tool changer and HS-3 robotic handling system



A_{II} – 7-axis robotic Polisher for Aspheres

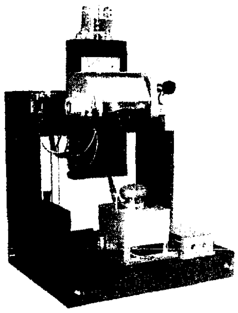
- Pre- and correction polishing of ground components, Ø 20 to 200 mm
- Uses conventional polishing media providing:
  - Low operating costs
  - Variable stock removal rates
  - High efficiency even in correction mode
- Different polishing patterns
  - Spiral
  - Raster
- Variable tool size and symmetric footprint
- Increased productivity by less corrections
- Precessions™ polishing controls mid spatial effects
- High form accuracy by prescriptive surface control using Tool Path Generator (TPG)
- Tool control function predicts & performs rapid corrective polishing
- For all optical materials

DATA



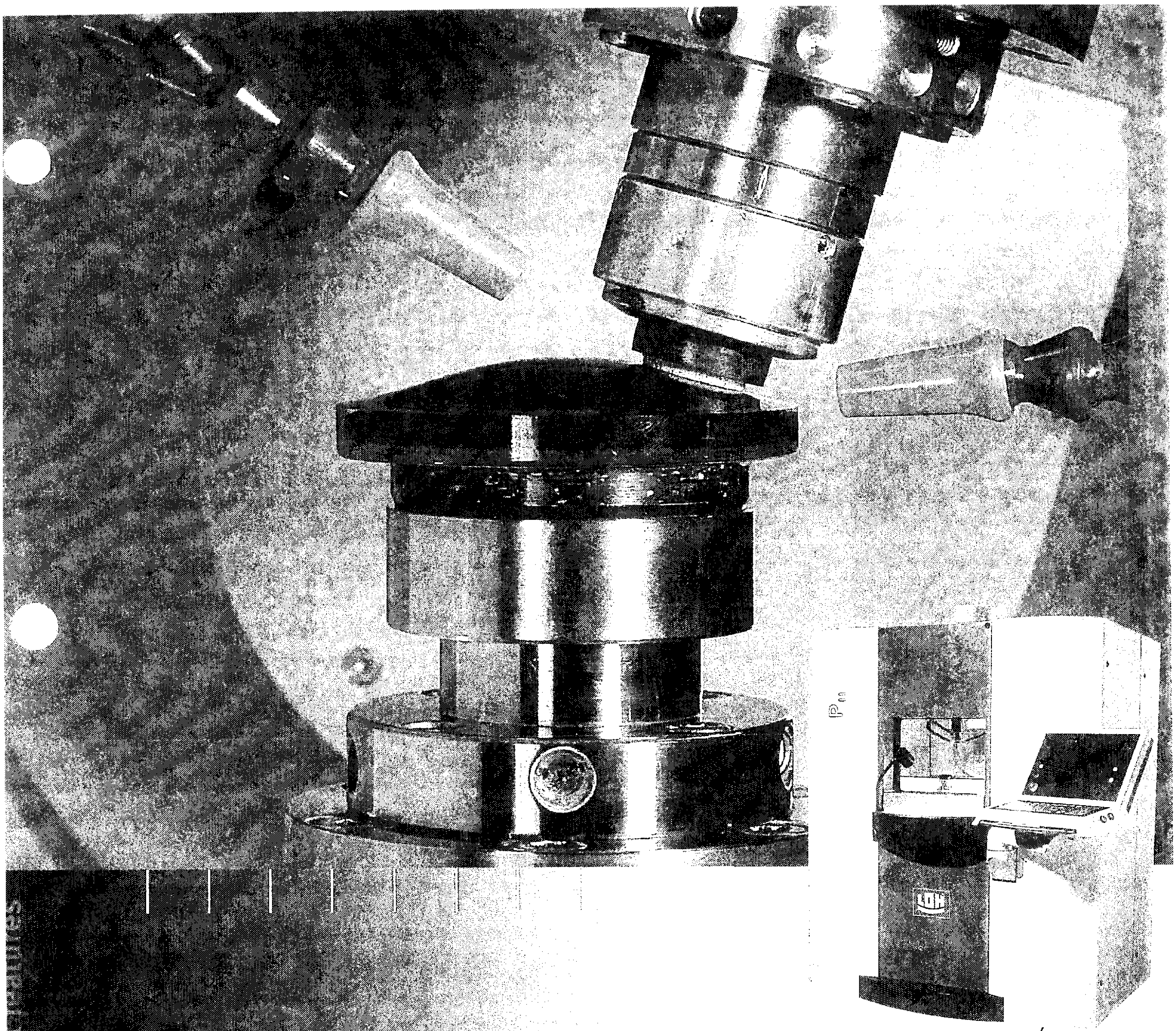
P_{II}–3A Polishing Aspheres

- **Dynamic process control** Dwell times, spindle speeds and polishing pressure can be set simultaneously
- **High rigidity, solid design,** compact construction
- **Integrated cleaning system** for the working chamber with separately controlled circuit
- **Spherical polishing** with Synchrospeed or Variospeed method Ø 20 – 280 mm without changing the user interface
- **Easy operation** and programming



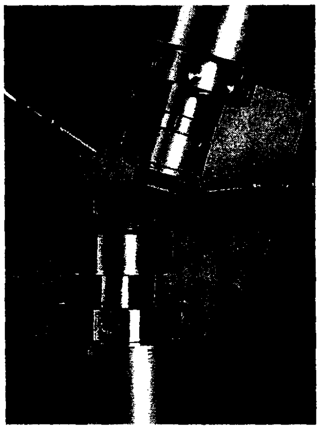
T_{II}–3D Topography Measuring Unit

- Unique – suitable for ground and polished surfaces
- Large working range
  - In aperture angle (hemisphere)
  - In departure to best fit sphere 2 mm
- Low operating costs using reference lenses
- Short set- up times
- Short measuring cycles
- Easy to calibrate and easy to use



Polishing of aspheres

P II A



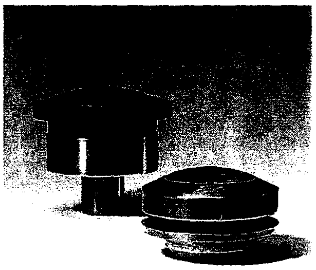
Features

- Polishing of aspheric surfaces of ∅ 20 – 200 mm (maximum aperture angle of 80°) as well as spheres ∅ 20 – 280 mm
- Control of the oscillation movement and of the tool positioning using different data concepts for the aspheric specification possible (incl. value tables).
- Polishing with flexible tools, customized tool design possible

Benefits

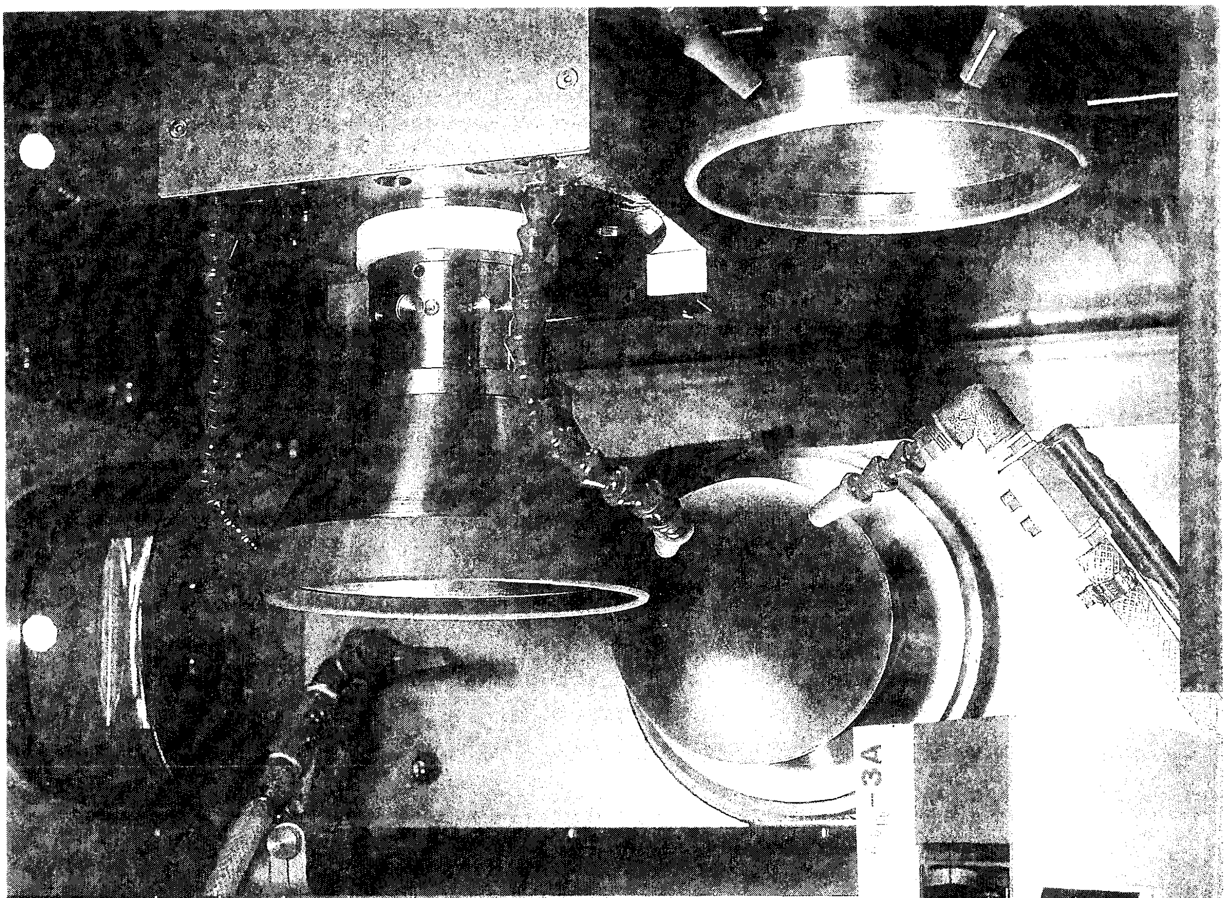
- **Dynamic process control** Dwell times, spindle speeds and polishing pressure can be set simultaneously
- **High rigidity, solid design,** compact construction
- **Integrated cleaning system** for the working chamber with separately controlled circuit
- **Spherical polishing** with Synchrospeed or Variospeed method ∅ 20 – 280 mm without changing the user interface
- **Easy operation** and programming thanks to graphic user interface and online diagnosis

DATA



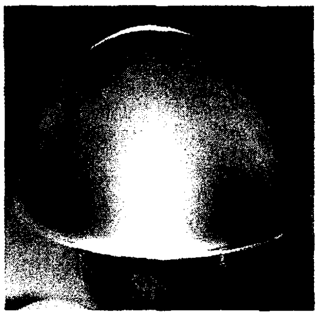
Technical data

- **Dimensions and weight**
  (w x d x h) 1600 x 1450 x 2280 mm
  Weight: 1,900 kg
- **Energy requirements**
  Electric.: 400 V / 50 Hz, 4.5 kVA
  Compressed air: 6 bar, 60 l/min



G_{II}-3 A

Pre- and fine grinding of aspheric surfaces



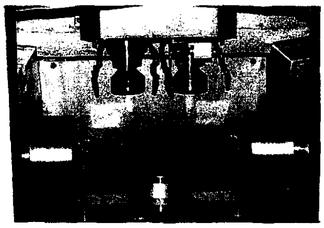
Features	Benefits

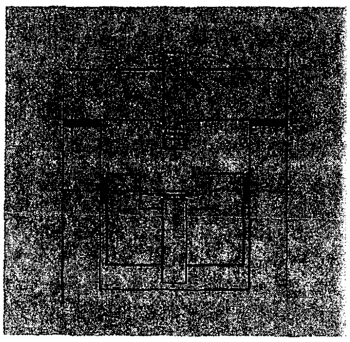
- Pre- and fine grinding of aspheric surfaces
  Ø 20 to 120 mm
- Generating of rotationally symmetrical aspheric surfaces with diamond tools in "single point" sensing.
- Pre- and fine grinding of spherical lenses Ø 20 to 120 mm ·

- Optimum adaptation to working different aspheric geometries since two working principles are used:
  - 3-axis control with diamond cup tools
  - 2-axis control with diamond wheel tools
- Reproducible accuracies thanks to rigit, solid and compact design
- Flexible data format: different options to describe the aspheric surface (incl. value tables)
- A variety of options to influence the process and correct shape errors
- Spherical, asphaerical processing and edging (chamfering and centering) can be combined within one job procedure, Ø 20 to 120 mm
- Easy operation and programming thanks to graphical user interface and online diagnosis

DATA

Technical Data

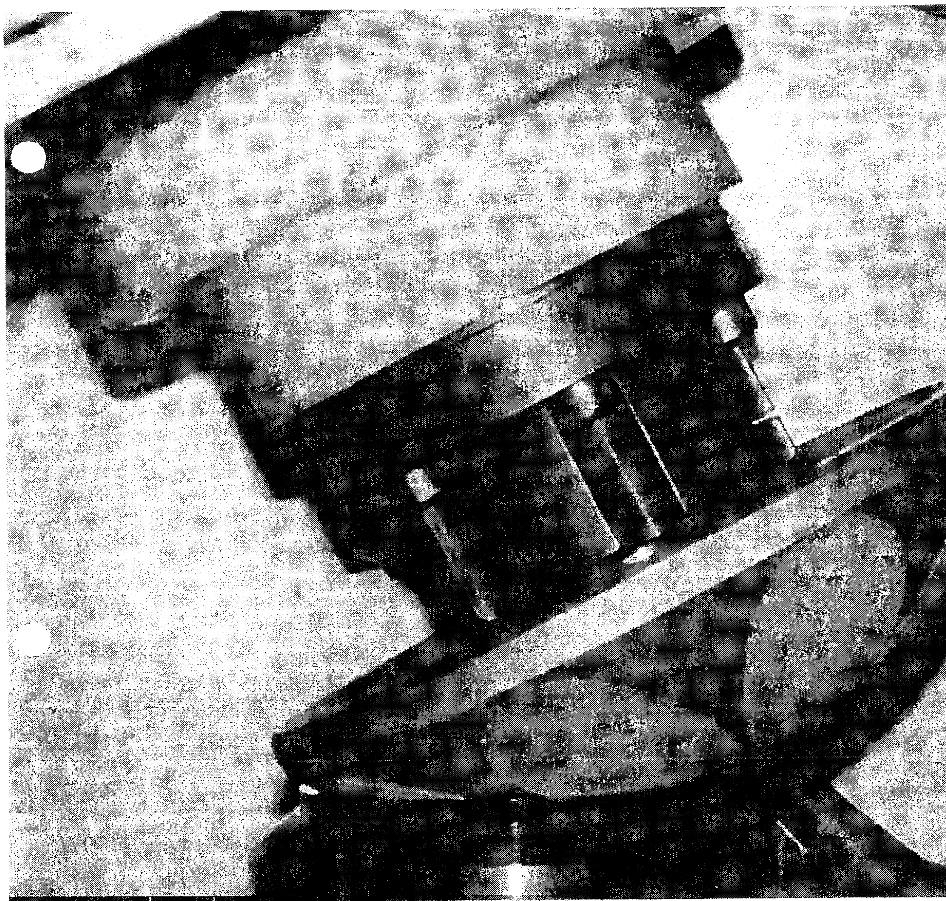




- **Energy requirements**
  Electric: approx. 10 KW, 200-550 V, 50/60 Hz
  compresses air: 6 bar
- **CNC-Axes**
  5 – 8
- **Dimensions & weight**
  - (w x d x h): 1,450 x 2,061 x 2,157 mm
  - Weight: approx. 3,700 kg

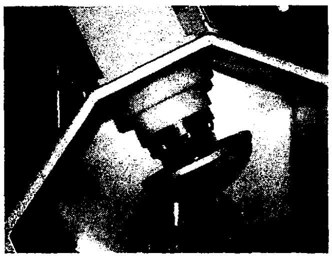
Options

- Tool changer
- Automatic tool clamping



Polishing spheres

K_{II}



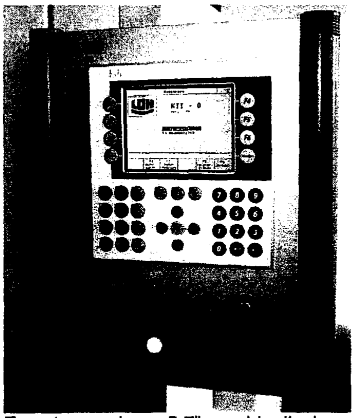
Features

- **2-spindle polishing machine for spheres** ∅ 10 - 100 mm
- **Convex, concave**
- **Features equivalent to CNC controlled polishing machines**

Benefits

- **Large working range with oscillation for lens radii convex/concave <= 150 mm**
- **Compact design**, only 800 mm wide
- **Easy to use large graphic display** similar to Loh-CNC machines
- **All axes automated** for intelligent job management
- **Automatic processing** with robotic loading system HS-3 (optional)
- **Low investment**
- **Robust design**
- **High reliability**

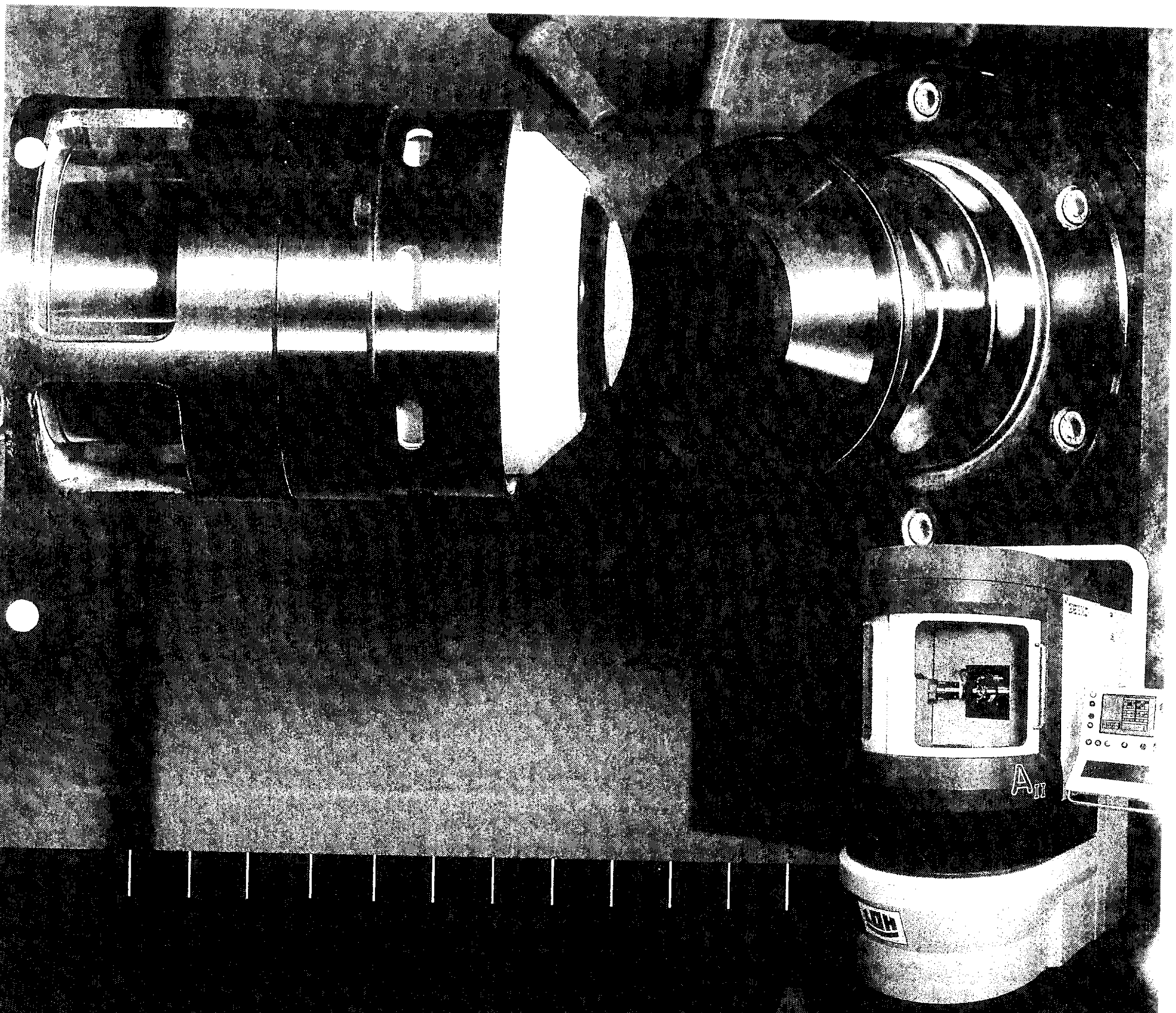
DATA



Easy-to-use, large 5.7" graphic display

Technical Data

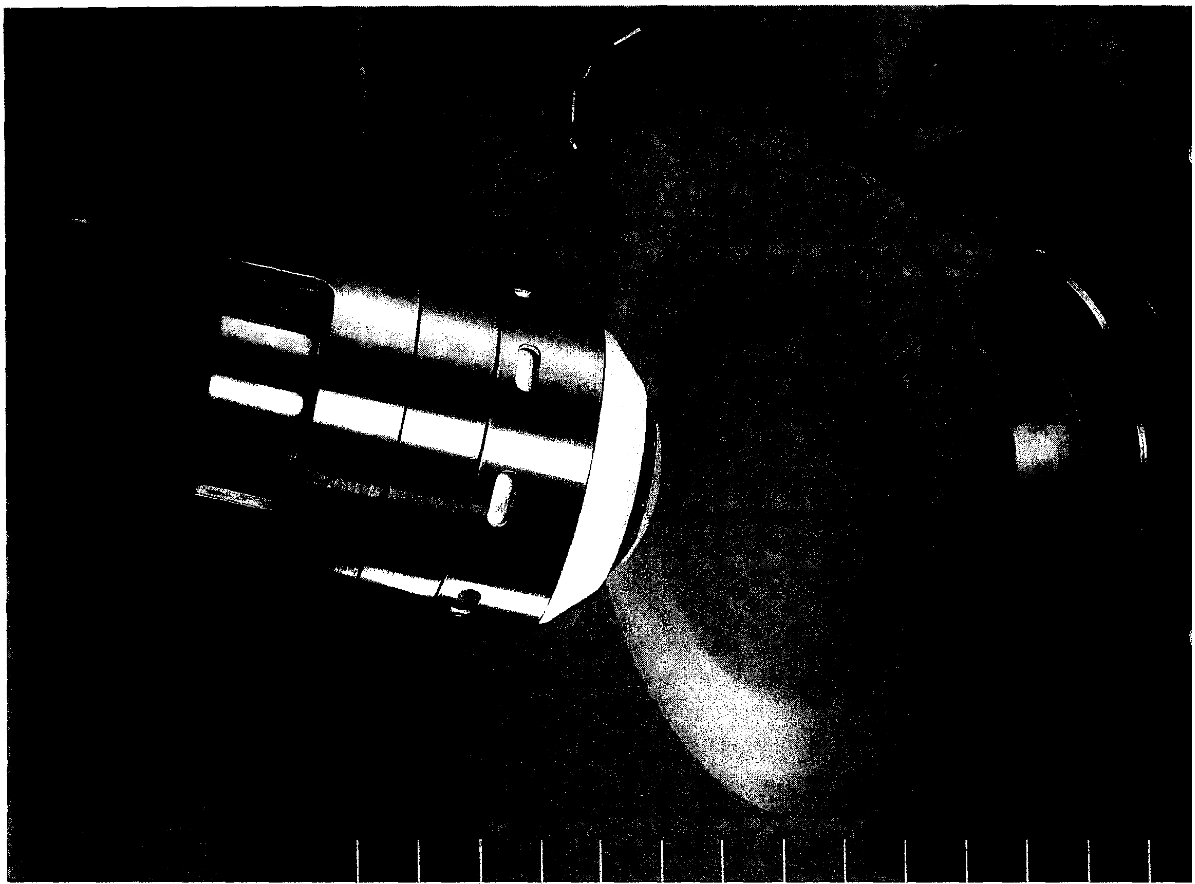
- **Working range**
  ∅ 10 - 100 mm,
  radii range: +/- 150 mm,
  pivoting angle: max. 50°, infinitely variable oscillation over whole displacement
- **Tool diameter**
  max. 210 mm
- **Control**
  SPS control, control panel with:,
  5.7" graphic display (monochrom),
  keyboard, machine control panel
- **Energy requirements**
  Electric:
  400V, 50 Hz, approx. 2.5 kVA
  Compressed air: 6 bar,
  consumption: 80 – 120 l/min
- **Dimensions & Weight**
  (W x D x H):
  800 x 1,250 x 1,800 mm
  Weight: 930 kg
- **Option:** robotic handling system HS-3
- **Conumables & Tools**
  Various polishes and tools available from Loh Opticservice.



A II

A fast & precise 7-axis flexible robotic polisher producing aspheres from ground or pre-polished components

LOH



A_{II} –

7-axis aspheric [illegible]

The A_{II} is an innovative and flexible robotic polisher designed to produce aspheres from ground or pre-polished components with speed and precision. It complements the Loh G-System for pre- and fine grinding of aspheres.
The A_{II} technology is flexible and easy to use. It adapts effortlessly to different component geometries and process conditions. Use of standard polishing slurries and cloths minimises costs.

Features
The A_{II} pre-polishes the ground blank, before corrective and finish polishing using the integrated Precessions™ software (with optimisation algorithm) for:
- Aspheres
- Spheres, plano optics & cylinders
- Prisms & other optical surfaces
- ∅ 20 – 200 mm

- **7-axis CNC control** enables automatic figure control and fast polishing of a wide variety of geometries
- **Breakthrough: patented polishing head** with pressurised membrane tool creates a precision controlled variable polishing spot
- **Polishes all standard materials** glass, ceramics, crystals, suitable metals, semi-conductor materials, composites
- **The predictive Precessions™ software optimises form correcting tool path data** based on an error map, which has been computed from design data & metrology information
- **Imports CAD lens design data** with interfaces being created for most standard industry software packages

Optimum surfaces with Precessions™ polishing

The Precessions™ technique creates a circular polishing spot which traverses the surface of the optic in either a spiral or raster pattern. The spot's removal function has a Gaussian footprint (as defined mathematically). Using this regular shape the software computes a tool control function first to predict and then to perform rapid corrective polishing using the variables of dwell time, spot size and tool pressure.

The Benefits:

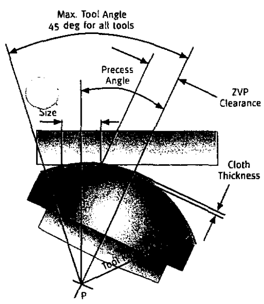
- **Effective form correction**
- **Precision form control**
- **Precessions™ also controls the mid-spatial effects** created by the polishing tool
- **Reduced correction iterations** using an advanced algorithm for corrective polishing lead to **increased productivity**
- **Shorter process cycles** by running form correction calculations off-line

Further benefits

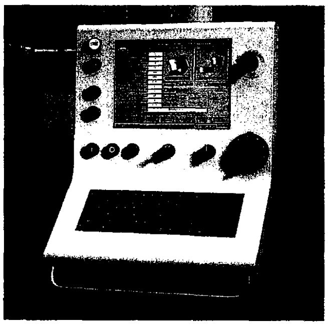
- **Integrated tool dressing and tool measurement functions**
- **Installed metrology** performs automatic machine axis and positioning calibration checks
- **High form accuracy by prescriptive surface control using Tool Path Generator (TPG)** to compute tool path, tool-size and dwell time information with respect to component and tool geometry, material removal functions and other variables
- **Low operating costs** as the A_{II} uses standard polishing media
- **Easy to understand** polishing concepts, controllable technology
- **High quality surface texture** with precessed tool technology
- **Rapid job changeovers** from the A_{II}'s flexible configuration
- **Precision control of the lens' centre and edge** by controlling the pressurized tool and other process variables

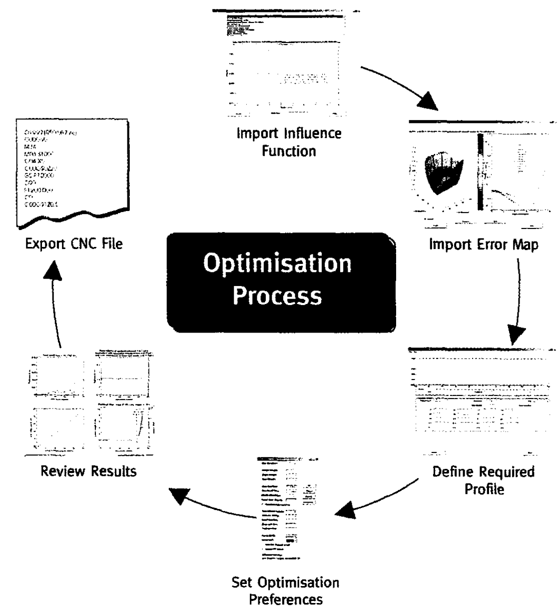
A_{II}

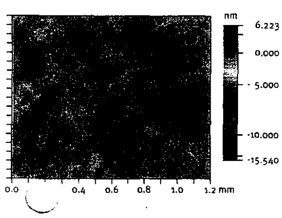
Precessed tool



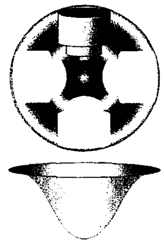
Easy to use touch screen with graphical interface







Typical surface texture result achieved by the process – Ra 0.5 nm



Typical Gaussian "Influence Function" created by a precessed tool

Technical Data

7 CNC-Axes

- Linear axes: X, Y, Z
- Rotational axes: A, B, C, H

Working range

- ∅ 20 – 200 mm
- Thickness: max. 75 mm
- Orientation: vertical

Materials

Any materials that can be polished by traditional means can be polished on the A_{II} including glass, ceramics, crystals, suitable metals, semi-conductor materials, composites and others.

Tool sizes

∅ 20 mm, 40 mm and 80 mm

User interface

Touch screen machine tool controller with friendly user interface. Both Tool Path Generator and Precessions™ optimisation software are included.

[illegible]

May be imported from the Loh T_{II} topography measuring device as well as commonly used instruments from e.g. Veeco/Wyko, Zygo and Taylor Hobson. Other interfaces can be prepared on request.

As yet achieved machine accuracies

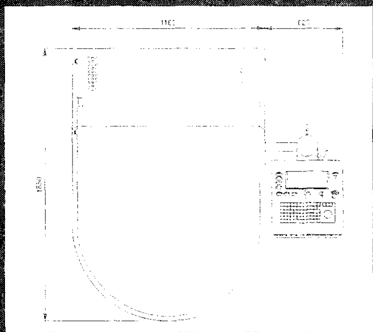
- Form accuracy: 80 nm p-v
- Surface finish: Ra = 2 nm Ra on BK7
- Controllable local polishing/figuring: removal rates varying from ‹ 0.05 mm^3/min. to 2.0 mm^3/min.

Energy requirements

- Electric: 400 V (+10 %, -15 %), 50/60 Hz, 8 kVA
- Compressed air: 6 bar, air consumption: approx. 130 l/min.

Dimensions & weight

- Dimensions: (w x d x h): 1,160 x 1,850 x 1,950 mm
- Weight: 1,800 kg



Footprint A_{II} (1,780 mm x 1,850 mm)

Accessoires

Slurry tank and slurry management system

Software interfaces to lens design packages and alternative metrology systems

Consumables

The A_{II} uses standard polishing slurries and cloths and saves on operating costs compared with other systems. A full range of slurries are available. Please ask your Loh representative of Loh's Opticservice division.

LOH
Loh Optikmaschinen AG
Wilhelm-Loh-Straße 2 – 4
Postfach 2069
D-35573 Wetzlar
Phone: + 49 (0) 6441 · 912 · 0
Fax: + 49 (0) 6441 · 912 · 130
E-Mail: loh@loh-optic.com
www.loh.de
www.loh-optic.com

1. ZERODUR® has extraordinary properties

ZERODUR® is a glass ceramic that Schott has developed for optical, opto-electronic and precision engineering applications. Through intensive material research and technology development this glass ceramic has become a material with extraordinary properties that can be supplied in blocks weighing several tons or as small components, both with unequaled precision. For this reason, ZERODUR® has become a performance and quality determining factor in many spectacular applications in modern technology.

- Mirror substrates for large astronomical telescopes (for example up to 8.2 meters in diameter)
- Mirror substrates for x-ray telescopes in satellites
- Optical elements for comet probes, weather satellites, and microlithography
- Frames and mirrors for ring laser gyroscopes
- Distance gauges in laser resonators
- Measurement rods as standards for precision measurement technology

What is ZERODUR® and how is it made?

ZERODUR® is an inorganic, non-porous material which has a crystalline phase and a glassy phase. Glass ceramic material is produced as follows:

Using methods common in glass technology, suitable raw materials are melted, refined, homogenized and then hot formed. After the cooling and annealing of the glassy blank a temperature treatment follows in which the glass is transformed into a glass ceramic through controlled volume crystallization. During this temperature treatment nuclei form within the glass, and crystals subsequently grow at a somewhat higher temperature. The crytalline phase and the glass phase together then lend the glass ceramic ZERODUR® its special properties.

Zero Expansion

ZERODUR® contains 70-80 weight percent crystalline phase with a high quartz structure. This has a negative linear thermal expansion, while that of the glass phase is positive. The special composition of the base glass for the glass ceramic ZERODUR® and defined nucleation and crystallization conditions result in a material with extremely low thermal expansion which in certain temperature ranges can even be zero or slightly negative, depending on the ceramization program.

Homogeneity and quality can be seen in ZERODUR®

ZERODUR® is a material of the highest homogeneity, and even in large pieces with dimensions of several meters displays thermal and mechanical characteristics with nearly unmeasureable deviations.
The very small crystals and the low difference in refractive index between the crystalline and glass phase result in good transparency in the spectral range from approximately 0.4µm to 2.3µm, a prerequisite for being able to test the internal quality of the material. No bubble, no inclusion and no striae remain undetected

Thus, both tiny precision parts and massive blocks made from ZERODUR® uniformly exhibit the same precise behavior.

ZERODUR®, unusual in its properties - easy to fabricate

Engineers and scientists are continually discovering the glass ceramic ZERODUR® as an ideal material for their very special tasks which call for the highest precision.

ZERODUR® has a completely non-directional structure, and it possesses a non-porous surface. Crystalline and glass phases have chemical characteristics and hardness similar to those of optical glass so that ZERODUR® can be processed using the same machines and tools as optical and technical glasses (for example: cutting, grinding and polishing).

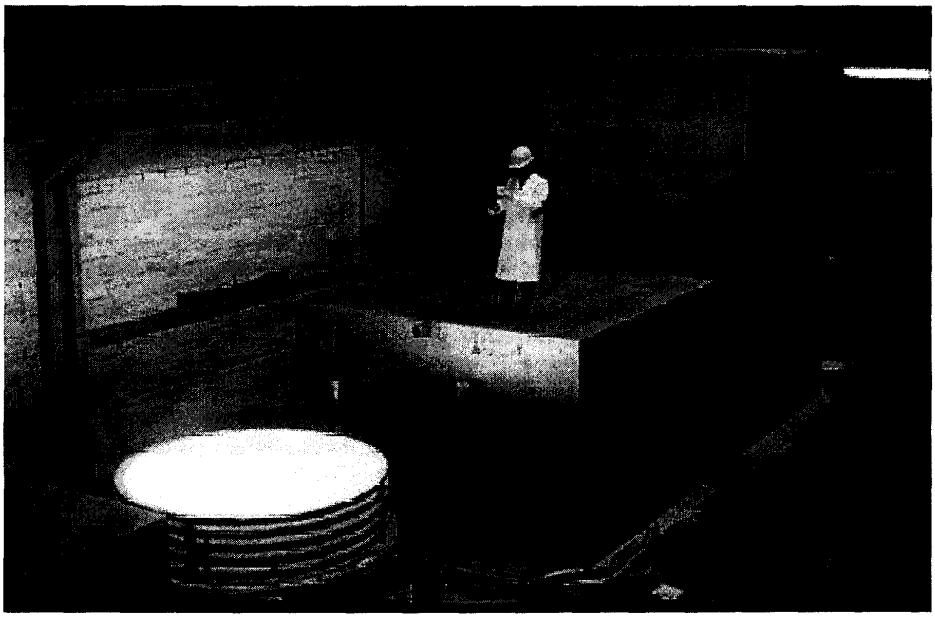
ZERODUR®, versatile in application

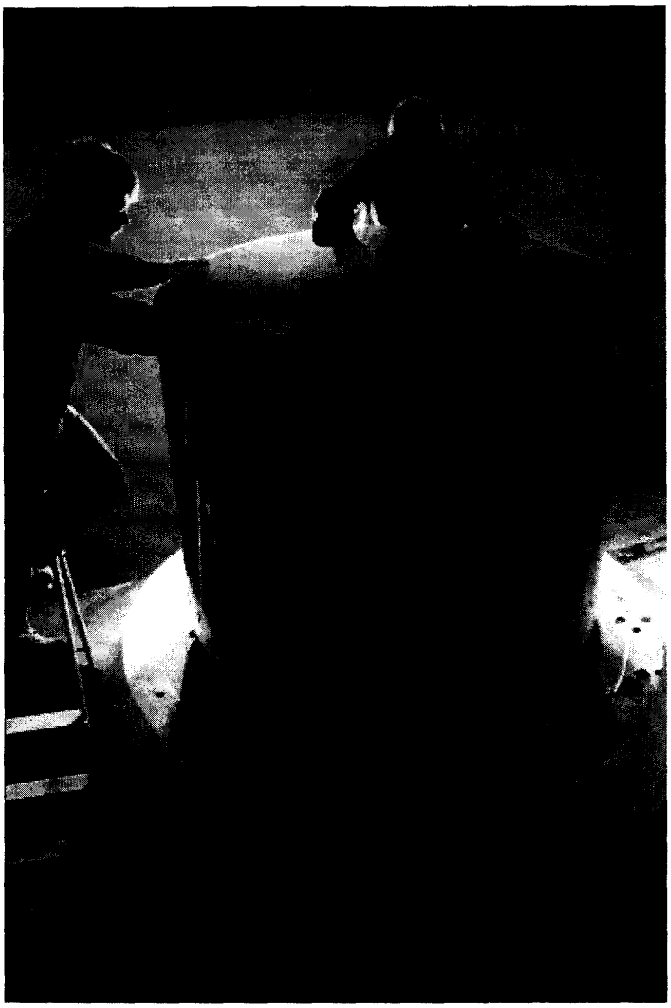
Therefore, ZERODUR® is the ideal mirror substrate for astronomical telescopes and x-ray telescopes where changes in the mirror caused by temperature would influence the quality of the observations. ZERODUR® assures that better optical performance can be acheived using smaller and lighter mirrors.

In ring laser gyroscopes ZERODUR® forms the temperature-independent frame. Low helium permeability provides for long life. In microlithography mirror subtrates and other important optical components of ZERODUR® allow for precise imaging of structures in the manufacturing of microchips.

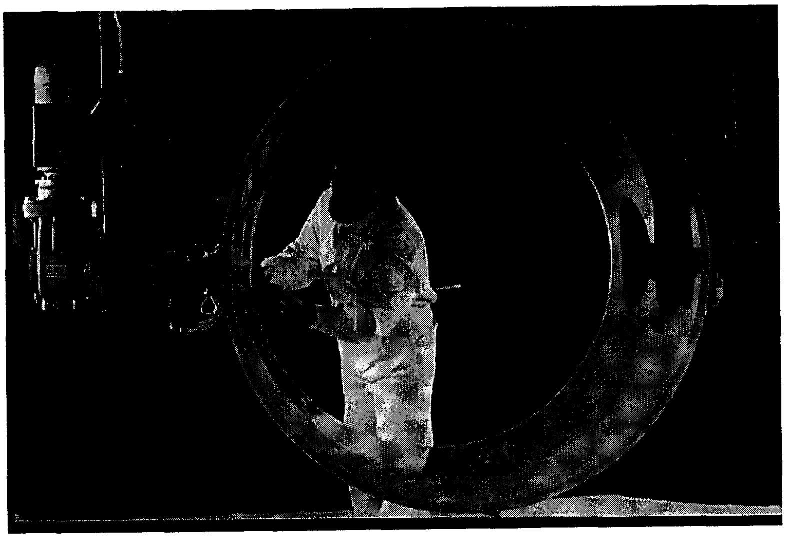
In laser technology, too, ZERODUR®'s unusual linear thermal stability is proven. ZERODUR® rods used as distance standards assure stable, exact calibration of the resonator distance despite temperature deviations during operation and increase the performance capability of the laser.

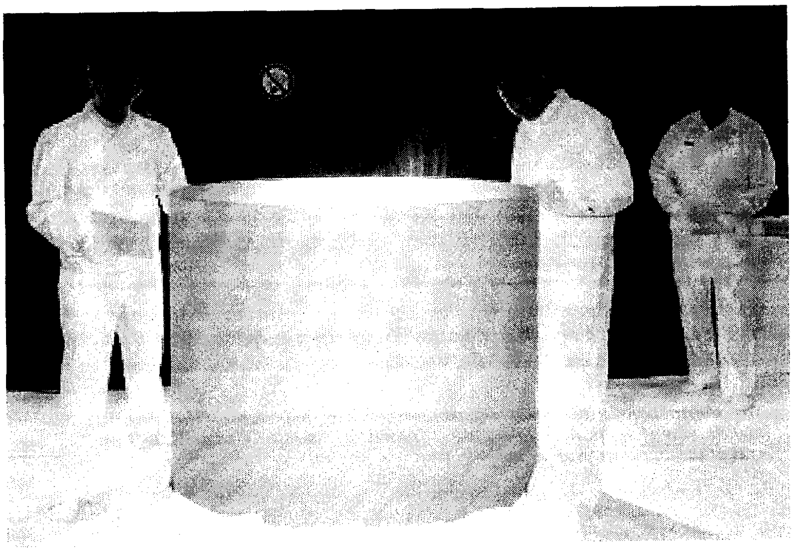
ZERODUR® is a glass ceramic which is subjected to precisely controlled months' long thermal process after being melted as glass in order to achieve zero thermal expansion. A 2-meter mirror blank pour is transported into the annealing furnace.





The mirror blanks for NASA's spaceborne x-ray telescope CHANDRA is manufactured from massive blocks using core drilling and grinding processes.





8 thin-wall conical hollow cylinders placed inside of and behind one another form the CHANDRA X-ray telescope. Using precise CNC-machining the material is processed to its very close dimensional and shape tolerances (0.1mm). A device developed by Schott allows the handling of the fragile body.

2. Thermal Properties

The most important and significant properties of the optical glass ceramic ZERODUR are the extremely small coeffecient of linear thermal expansion as well as the homogeneity of this coefficient throughout the entire piece.

Mean coefficient of linear thermal expansion

Individual pieces of ZERODUR (discs, plates, rods) can be supplied with a mean coefficient of linear thermal expansion α in the temperature range 0°C to 50°C in three expansion classes as follows:

Expansion Class 0	$0 \pm 0.02 \cdot 10^{-6}$/K
Expansion Class 1	$0 \pm 0.05 \cdot 10^{-6}$/K
Expansion Class 2	$0 \pm 0.10 \cdot 10^{-6}$/K

f not otherwise expressly specified, material up to Expansion class 2 will be supplied. Closer tolerance will be supplied upon request.

Figure 1 illustrates the typical coefficient of linear thermal expansion a. ZERODUR exhibits a very slight linear expansion over the entire temperature range. It is especially low in the room temperature range.

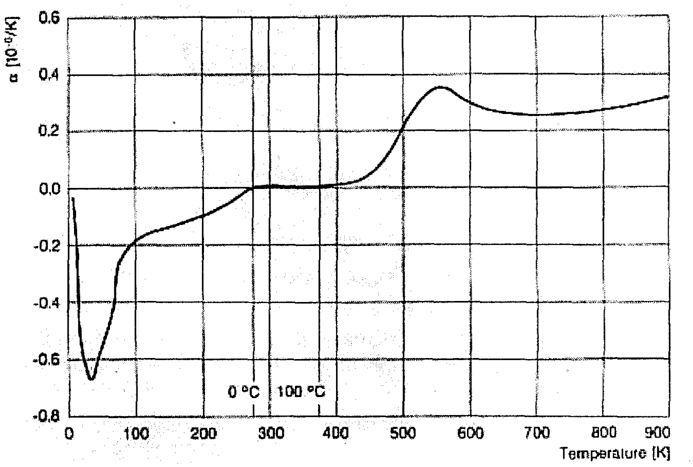


Figure 1: Curve of coefficient of linear thermal expansion α of *ZERODUR*

Homogeneity of the coefficient of thermal expansion

The glass ceramic ZERODUR exhibits excellent homogeneity of the linear expansion coefficient within the respective volume of a disc, plate or block. The stated tolerances for homogeneity of linear expansion can be guaranteed in the following weight classes for each part, provided that the diameter of the part is at least twice its thickness:

up to 18 tons	$\leq 0.03 \cdot 10^{-6}$/K
up to 6 tons	$\leq 0.02 \cdot 10^{-6}$/K
up to 0.3 tons	$\leq 0.01 \cdot 10^{-6}$/K

The measurement accuracy for a in the temperature range of 0°C to 50°C is $\pm 0.01 \cdot 10^{-6}$/K, the precision under repeatability conditions is $\pm 0.005 \cdot 10^{-6}$/K.

Total change of length is a specified temperature interval

In certain applications the total change of length of α ZERODUR® part within a specified temperature interval is vital to its function (such as laser gyroscopes). In the region of -50°C to +100°C it is usually smaller than $10 \cdot 10^{-6}$, based on the total length of the part.

Upon request ZERODUR® can be supplied with smaller values. Material with the smallest attainable value for the total change of length has a slightly positive mean expansion coefficient Δl/l (0°C to 50°C) of approximately $+0.02 \cdot 10^{-6}$/K

Figure 2 shows the typical relative expansion in length Δl/l of ZERODUR® relative to 0°C. The measurements were performed by CSIRO (National Measurement Laboratory in Sydney, Australia) in the temperature range 2K to 125 K and made by Schott in the temperature range of 90 K to 900 K.

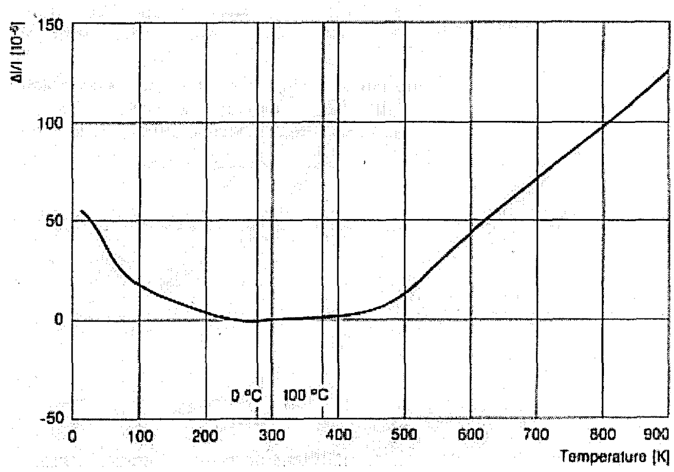
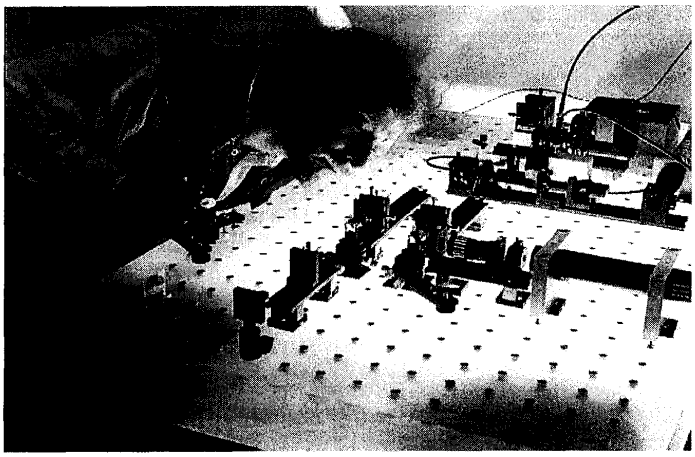


Figure. 2: Relative linear expansion Δl/l of ZERODUR®

Vibration-free mounted table tops made of ZERODUR® enable very precise micropositioning of optical components. Changes in distance caused by temperature fluctuations are avoided.



Thermal conductivity

The measured (—) and estimated (---) values of thermal conductivity λ are shown in Figure 3.

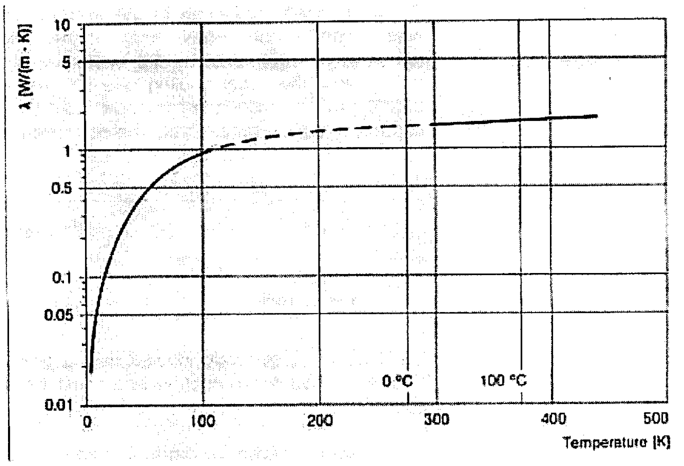


Figure 3: Thermal conductivity λ of ZERODUR® as a function of temperature.

Thermal conductivity λ at 20°C [W/(m·K)] ______________ 1.46
Thermal diffusivity index a at 20°C [10^{-6} m²/s] ______________ 0.72

Heat capacity c_p

The measured (—) and estimated (---) values of heat capacity c_p are shown in Figure 4.

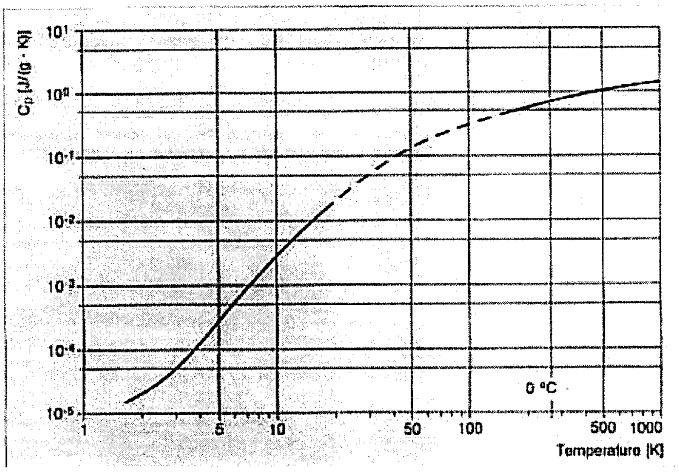


Figure 4: Heat capacity of ZERODUR® in relation to temperature

c_p at 20°C [J/(g·K)] ______________________________ 0.80

Maximum application temperature

ZERODUR® may be used as a mechanical component as well as a window at temperatures up to 600 °C.

Slight changes may arise in the thermal linear coeffiecient a (0°C to 50°C) which can affect components of the highest optical precision, due tc temperature treatments by the customer or user. If the final cooling rate RE differs from the initial cooling rate RP, especially in the temerature range ol 320°C to 130°C, the change of the coefficient of linear thermal expansion a (0°C to 50°C) can be estimated by using the following equation:

$$\Delta\alpha\ (0°C \text{ to } 50°C) = 0.025 \cdot \log_{10}\left[\frac{R_E}{R_P}\right] \cdot 10^{-6}/K$$

R_P: Initial cooling rate
R_E: Final cooling rate

ZERODUR® is generally cooled during production at an initial cooling rate of 0.1K/min. This initial cooling rate must be checked and confirmed in critical cases.

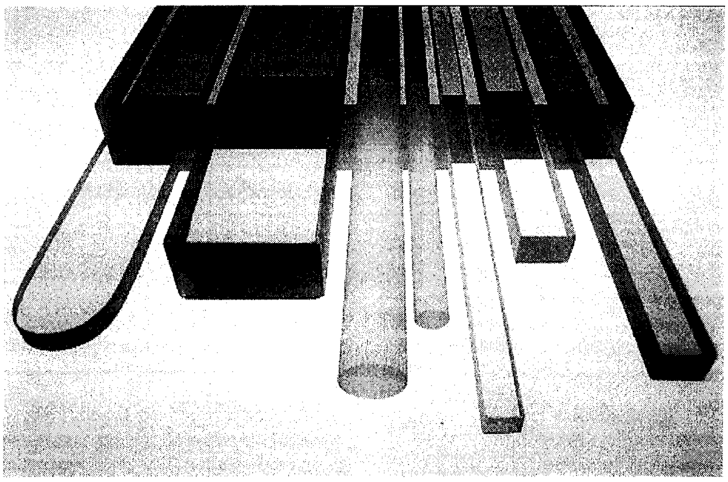
The linear coefficient of thermal expansion does not change when the cooling from the temperature above 320 °C carried out at the same rate as the initial cooling. The glass ceramic ZERODUR® can be subjected to temperature treatments up to 130°C without causing changes in the expansion coefficient a (0°C to 50°C).

ZERODUR® M

In the event of highest thermal expansion quality demands we ask for further inquiry if it is possible to avoid cooling rates other than 0.1K/min (or an initial cooling rate) in the critical temperature region during processing or use ol ZERODUR®.

If a customer cannot influence cooling rate, we recommend considering the use of ZERODUR® M, a material variation ZERODUR® (see product information No 10008).

Rods and slabs without thermal expansion are the subtrate of choice for measurement scales, standards and on precision measurement technology.



3. Mechanical Properties

Length stability over time

Since 1973, 400mm long gauge blocks made from ZERODUR® have been interferometrically connected to an wavelength standard at the PTB (Physikalisch-Technische Bundesanstalt, Germany). The rods are maintained at 207°C and are shortened slightly but regularly. Interpolation formulas that have been derived from previous mesurements on the basis of theoretical consideration allows predictions to be made for the expected change in the length of ZERODUR® relation to time.

In a formal analogy to the thermal linear expansion coefficient α the following applies:

$$l = l_0\,(1 + A \cdot \Delta t)$$

l_0 = Sample length in the initial state
A = Length aging coefficient
Δt = Time interval
l = Sample length after the time Δt

The value of A is always negative for isothermal storage. It depends on the cooling process and on the age of the sample and has an order of magnitude of $|A|<10^{-7}$ per year.

Young's modulus E

The Young's modulus for a typical melt is shown in Figure 5 as a function of temperature.

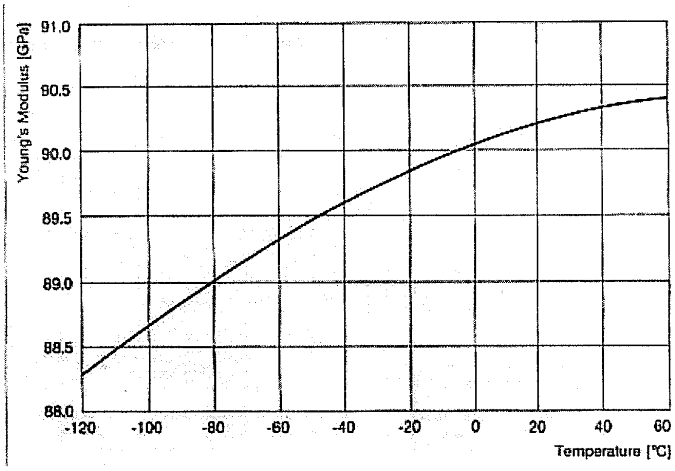


Figure 5: The Young's modulus of in relation to temperature for a typical melt

Young's modulus E at 20°C [GPa]-mean value_______________90.3

Bending strength

The practical bending strength of glasses and glass ceramics is not a material constant. It is particularly upon the following factors:

- Micromechanical condition of the tension loaded surfaces
- Size of the tension loaded surfaces subjected to stress
- Rate of load increase
- Surrounding medium, usually air

Except for individual samples the bending strength is listed as the failure probability (Weibull distribution). measurement is performed according to the double-ring test described in DIN 52 292 Part 1 Figures 6 and 7 show the failure probability for ZERODUR® samples after processing of the test surfaces with diamond tools (bonded grit) and with loose SiC grit, each with different grit sizes.

(The area of each test surface subjected to bending stress equals S_L = 113 mm²; the rate at which the stress is increased is σ_b = 2 Mpa/s = 2N/(mm²·s). The sample is surrounded by air.).

Grit Designation		Grit Size	
FEPA	US Mesh ASTM E 11	Mean [µm]	Maximum [µm]
D 251	60/ 70	231	250
D 151	100/120	138	150
D 64	230/270	58	63
D 35	325/400	36	40

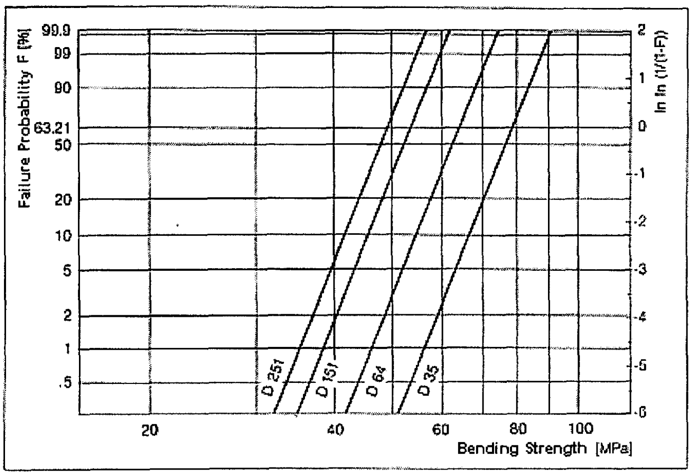


Figure 6: Failure probability for test surfaces processed with bonded grit of different sizes

Designation SIC- Abrasive FEPA	Grit Size	
	Mean [µm]	Maximum [µm]
100er	106 - 125	149
230er	50 - 56	82
320er	28 - 31	49
600er	8 - 10	19

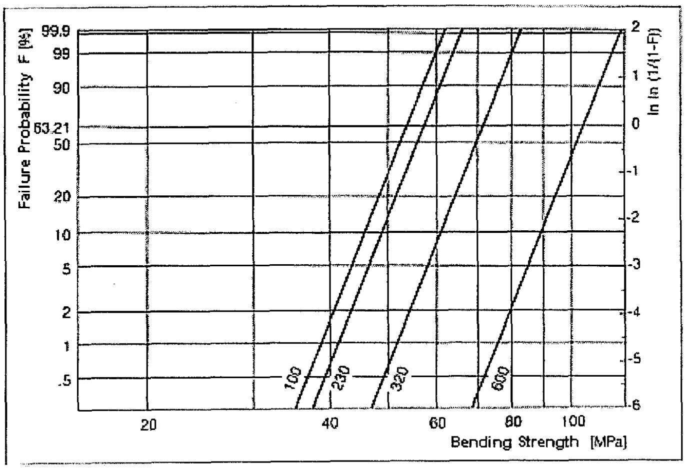


Figure 7: Failure probability for test surfaces processed with loose grit of different sizes

Figure 8 shows the bending strength of ZERODUR® samples as a function of the size of the test surface S_L.

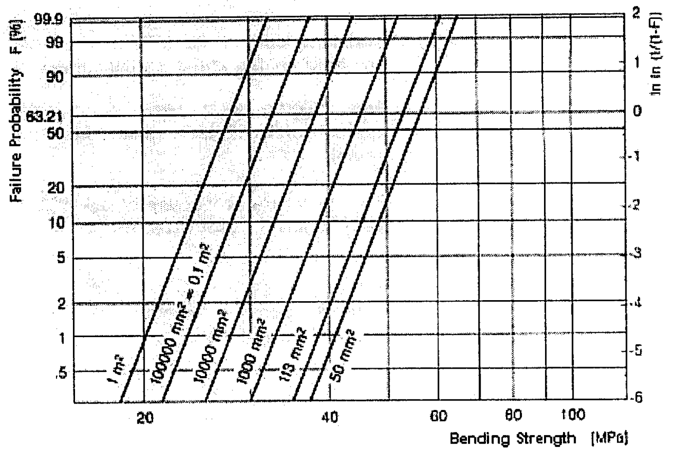


Figure 8: Failure probability F as a function of test surface area S_L.

The values for the test surface areas S_L=113mm 2; are based on measurements (Rate of stress (symbol)=2MPa/s. Test surface processed with D 151, air as the surrounding medium.).
The values for the other test surfaces are based on calculations.

In practice the bending strength is often needed for a load constant in time and not for defined load increases - as it measured in the laboratory. From the nomogram in Figure 9 the bending strength under constant load can be derived from the bending strength for a load increasing at 2 MPA/s. The admissible constant load decreases as loading increases.

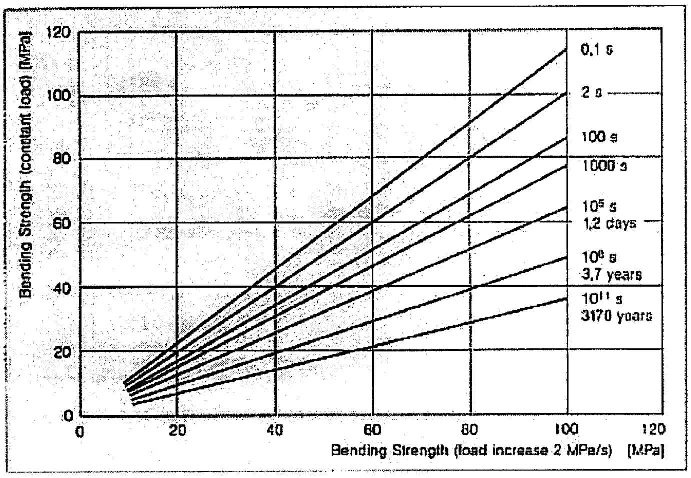


Figure 9: The bending strength of ZERODUR® under constant load

Application example

Requirement:

Constant load of 20 MPa over a period of three years with a failure probability of 5% and a loaded surface of 113 mm².

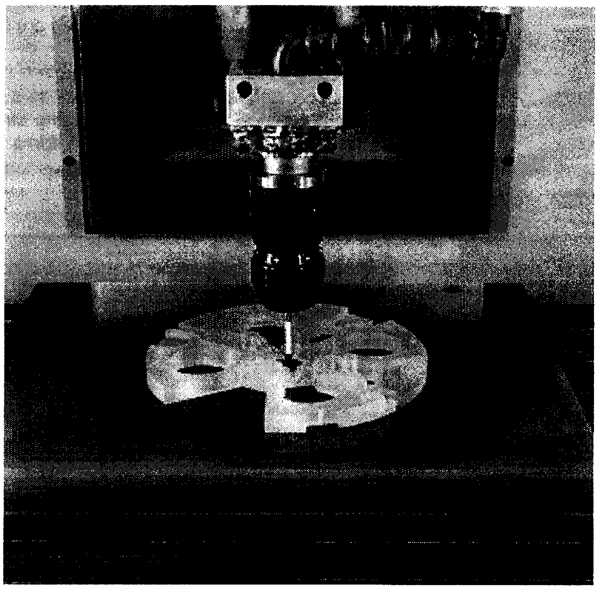
From Figure 9 a bending strength under laboratory conditions of approximately 42 MPa results from the straight line 10^8s (approximate 3 years).

For the failure probability of 5% it can be derived from Figure 6 that the sample must be processed with D 151 or finer to assure the value.

In many applications a value of 10 MPa can be assumed as a calculation value for bending strength. This applies, example, to small objects with scratch-free surfaces.

Other mechanical characteristics

Poisson's ratio μ	0.243
Density ρ [g/cm³]	2.53
Knoop Hardness HK 0.1/20 according to ISO 9385	620



High precision machining for complex structures

TRIOPTICS

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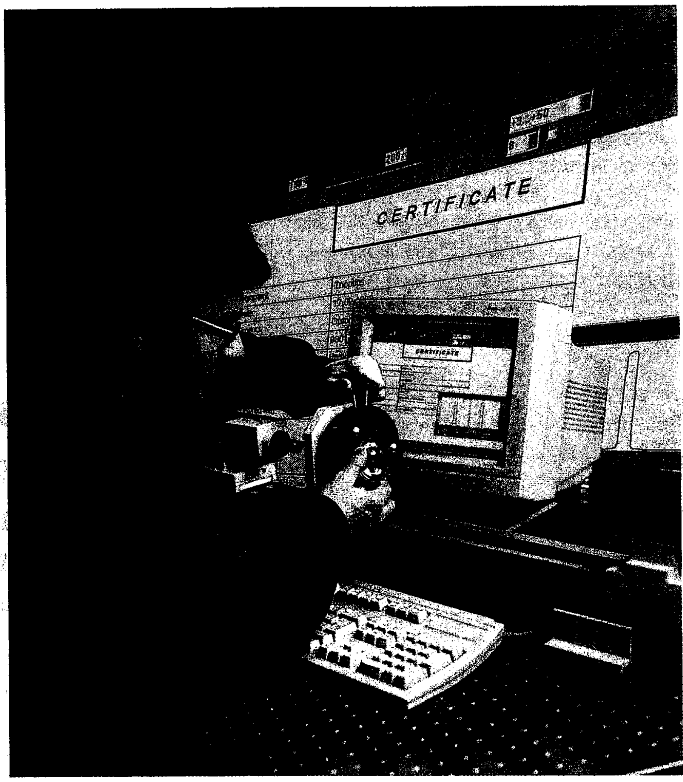
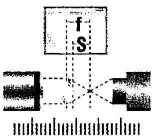
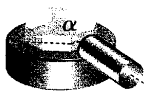
OPTICAL TEST INSTRUMENTS

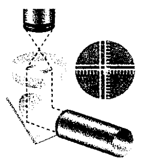


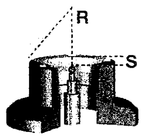


OPTICAL TEST STATIONS



GONIOMETERS


CENTRATION MEASUREMENT



SPHEROMETERS

OPTOMATIC AND OPTOMATIC MICRO

DESCRIPTION

OPTOMATIC is the first fully automated optical test instrument featuring rapid, ultra-accurate and objective performance characterization of a wide variety of optical components and lens systems. Responding to customer requirements for increased speed and accuracy in measurement of optical parameters, OPTOMATIC provides dramatically increased overall accuracy and software control of the complete measuring procedure.

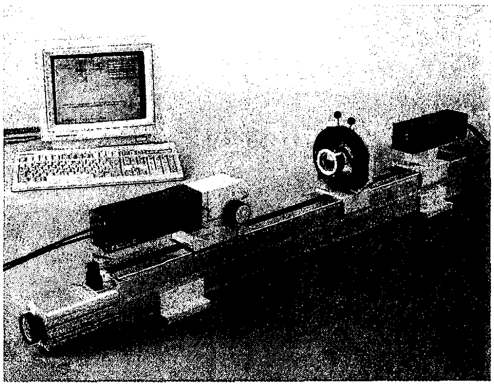
OPTOMATIC is horizontally set up and recommended where a large variety of lenses has to be measured.

OPTOMATIC MICRO is vertically set up and designed to perform measurements of smaller optical components and systems. Due to the vertical set up it is also perfectly suited for measurement of centration errors.

APPLICATIONS

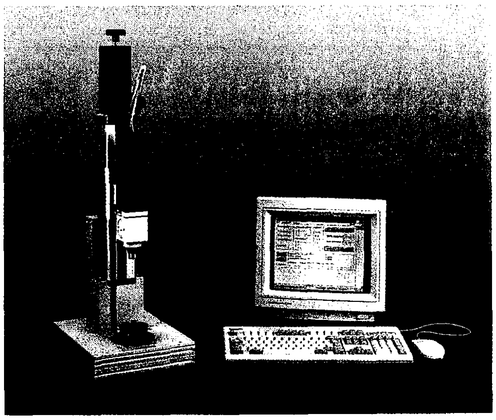
OPTOMATIC has been designed to measure a wide range of optical parameters related to almost all typical optical components and lens systems.

- **Effective Focal Length**
  The Effective Focal Length (EFL) can be measured for all positive and negative lens systems with focal length from 5 to 1200 mm. Virtually any existing lens systems ranging from high performance photographic lenses and microscope objectives to endoscope, ophtalmic lenses, singlets and doublets or molded plastic lenses can be accurately measured.



OPTOMATIC

- **Back focal length**
  Using a CCD-autocollimation head the BFL of positive and negative systems can be measured. In special set up, the radii of curvature can be measured as well.



OPTOMATIC MICRO

- **Flange Focal Length**
  OPTOMATIC provides ideal measuring capabilities for Camera Testing i.e. Flange Focal Length (FFL). The step motor driven Auto-Focus System and the computer controlled data acquisition permit quick, accurate and automated serial measurements.

TRIOPTICS
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- **Centering Errors**
  The centering errors can be measured either in transmission or in reflection. The centering errors will be displayed as axis deviation with accuracy of 1µm and the corresponding angular deviation of the transmitted or reflected ray.

- **Angles and Power of Wedges**
  The unique versatility of OPTOMATIC is underlined by the capability to measure not only parameters of lens systems but angles and power of wedges and 180°-prisms or pentaprisms.

- **MTF-Measurement**
  OPTOMATIC is capable to perform on-axis MTF-measurements in tangential plane with a spatial frequency up to 100 lines/mm. In this way the user has a convenient option to evaluate the image quality of optical systems tested for EFL or FFL.

SPECIFICATION

- Fully automatic and computer controlled measuring process
- Menu driven software (Windows 95)
- Focal length range:5...1200 mm
- Focal length range:1...250 mm*
- Accuracy: 0.01% to 0.3%
- Lens diameter:1...75 (100) mm
- Measurement time: 3-5 sec.
- Angle measuring range approx 1°
- Angle measuring accuracy: 1 arcsec.
- Optical power accuracy: +/-0.002 dpt.
- Centering error :+/-1 µm
- MTF Test mode: automatic, on-axis Spatial Frequency :0-100 lp/mm

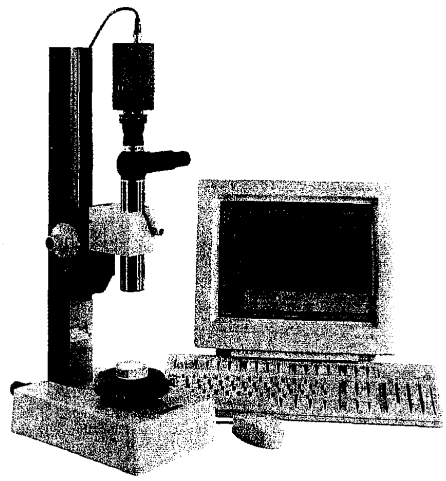
* Values for OPTOMATIC MICRO

AUTOMATED OPTICAL STATION OptiAngle

DESCRIPTION

OptiAngle is a PC-based Optical Test Station that can accurately measure angular displacements, centration errors and other parameters of optical components and systems.

To achieve this, the system incorporates visual autocollimators and CCD-Cameras connected to PC-frame grabbers. User-friendly Windows-based software guides



the user, improves dramatically the measurement accuracy and provides advanced data management. A large variety of modular optical and mechanical accessories extends the range of applications. This modular approach enables OptiAngle to be configurated or upgraded according to the operator's requirements.

ADVANTAGES

Compared to the visual optical testing, the image processing software provided with OptiAngle offers a lot of advantages:

- increased accuracy by approx. factor 10
- measurement of high speed rotating samples
- it enables the measurement of small or anti-reflex coated samples
- it features automatic measurement sequence with free selectable parameters
- extremely fast measurement: 1-2 seconds
- high reproducibility of the measurement results irrespective of the operator's qualification
- the measurement results can be stored or printed out

APPLICATIONS

PLANO OPTICS

- wedge angle
- 90°-angle of prisms
- absolute measurement of 45°-angles
- parallelism of plane plates
- deviation angle through wedges and prisms
- pentaprisms angle
- mirror tilt

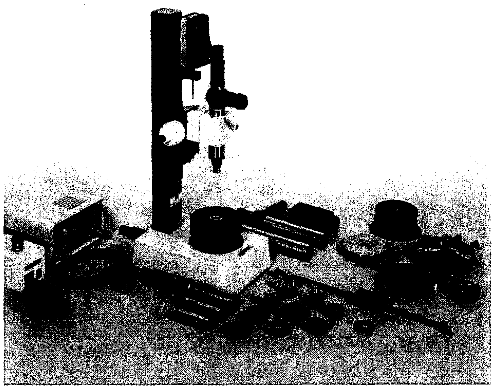
SPHERICAL OPTICS

- centration errors measured in transmission and reflection while the sample is freely rotated can be measured fast and accurate.
- cementing of lenses and achromats

The versatility of OptiAngle is underlined by further applications as measurement of :

- radii of curvature
- back focal length (BFL)
- effective focal length (EFL)
- resolution or image quality

A typical application is the measurement of back focal length and resolution efficiency



for intra ocular lenses (IOL's). A specific set up of OptiAngle known as IOL Optical Bench is ideally suited for quality control in production areas.

CD's and CD-ROM OPTICS

- alignment of CD-optical heads
- wobble of rotating glass disks

SYSTEM OVERVIEW

The system components of OptiAngle are of modular design so that for specific applications the components can be selected and set up by the customer. For typical applications complete packages are available:

4-100-00	OptiAngle for PLANO and SPHERIC components
4-100-01	OptiAngle PLANO
4-100-02	OptiAngle SPHERIC
4-100-04	OptiAngle VISUAL
4-100-06	IOL Bench

SPECIFICATION AND FEATURES

- Angle resolution: 0.2 to 2 arcsec depending on autocollimator and measurement type
- Centration errors: 1 to 5 microns depend-

ing on the measuring configuration.

- Focal length range: +500 to -500 mm. Accuracy: 0.3 to 0.5%
- Radii of curvature: concave/convex: 3 to 300mm (extension upon request). Accuracy: 0.02 to 0.5%
- BFL: 3 to 300 mm. Accuracy: 0.05 to 0.5%
- Sample diameter: 0.5 to 75 mm (100mm)
- Measurement time: 1 sec to 5 sec.
- Measurement wave length: centered on 546.1nm.
- Operation systems for software: WINDOWS® and WINDOWS NT®
- Software language: free selectable in German and English.
- Angle units free selectable
- On site calibration procedure.
- Real time monitor display of the autocollimator image
- Computer generated single cross for initial alignment
- Computer generated tolerance circles or angle graduations for quick checking of production quantities
- Automatic threshold i.e. automatic adjustment to the sample reflectivity
- Info-window displaying the current measurement parameters: mean value, standard deviation, selected measurement parameter, etc.
- Storage, loading or export of files and print out of the measuring certificate

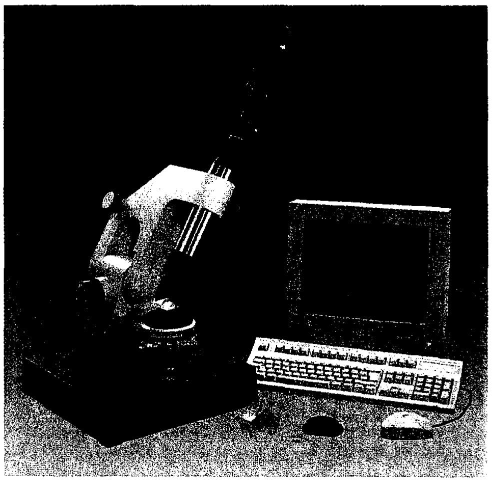
PRECISION GONIOMETERS

DESCRIPTION

For accurate measurement of PRISMS, POLYGONS, WEDGES, WINDOWS, PLATES etc. TRIOPTICS provides two precision goniometers :

COMPARISON GONIOMETER

The Comparison Goniometer usually needs a reference prism with a known angle. The Comparison Goniometer takes a first reference measurement using the master prism. Further measurements are made relatively to the angle of the master prisms.



The system includes an autocollimator mounted on the swivel arm and a collimator in the ground plate.

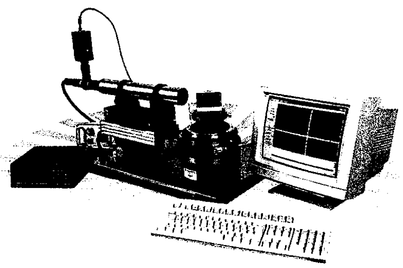
The autocollimator image is taken by a CCD-camera and further processed via framegrabber, PC and specific software. Measurements in reflection and transmission are possible.

The PC-controlled Comparison Goniometer features high accuracy and extremly short measurement time .

A prism measurement takes just the time to press a key of the PC. Being accurate, extremly fast and non-expensive, the Comparison Goniometer is perfectly suited for production environment and larger quantities of pieces.

Prism Master

The Prism Master features accurate measuremets of prisms angles from 0° to 360°. It incorporates a precision rotary table and Heidenhain rotary encoder whose cumulative error is within 0,2 arcsec. The fine rotary adjustment of the table is given by a high precision micrometer or a precision drive. A digital display provides an angle indication with a resolution of 0.1 arcsec. The instrument is computer controlled. The software provides easy operation, records of measurement data to a file and print out of the measurement certificate. The



Prism Master does not need a master prism, however, the measurement time and the costs are higher compared with the Comparison Goniometer.

SPECIFICATION

	Comparison Goniometer	Prism Master
Measuring Range	0°-360°	0°-360°
Master prism	required	not required
Resolution	0,1 arcsec	0,1 arcsec
Accuracy	± 1 arcsec (with ACM 500)	± 0,5 arcsec
Measurement Mode	Reflection and Transmission	Reflection (Transmission with special accessory)

OPTITEST

DESCRIPTION

The optical testing usually requires a wide range of set-ups (configurations) specific to the application or the parameters to be measured.

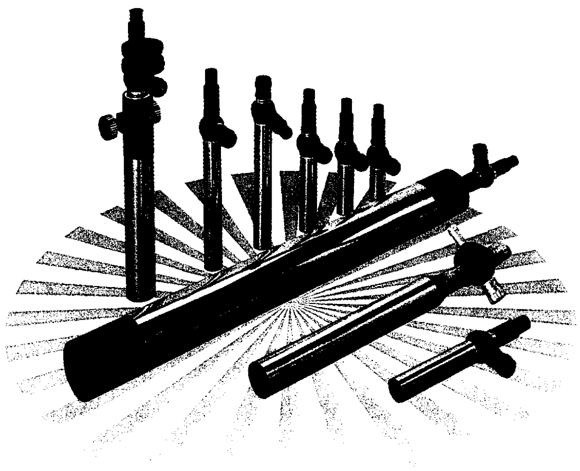
To cover the multitude of applications in the field of optical testing, TRIOPTICS developed the OPTITEST which is a comprehensive line of equipment including the largest range of basic optical instruments and additional mechanical hardware.

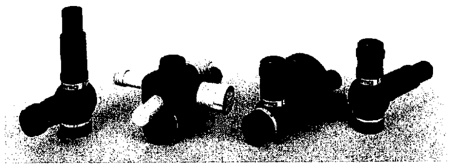
To cover all conceivable testing set-ups, the components of OPTITEST line are featuring a modular design i.e. are interchangeable and compatible with each other. The OPTITEST line, which is continuously developed, includes a large number of optical instruments:

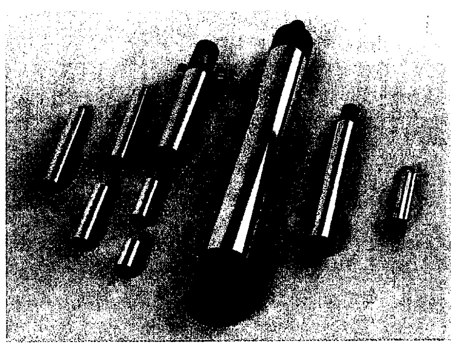
- Collimators
- Focusing Collimators
- Telescopes
- Focusing Telescopes
- Visual and computerized Autocollimators
- Autocollimators with Eyepiece Micrometers
- Focusing Autocollimators
- Focusing Autocollimators with Eyepiece Micrometers
- Large Field Autocollimators
- LED-Autocollimators
- Diopter Telescopes
- Dynameter
- Binoculars Testing Instrument
- Square Body Telescopes and Collimators
- Positionning Equipment
- Reticles

Type	Focal length (mm)	Tube diameter (mm)	Free Aperture (mm)	Magnification	Field of View*	Resolution (arcsec)
COL 100-38 TEL 100-38 ACM 100-38	100	38,1	30	6,4 x	6° / 3°	10
COL 150-38 TEL 150-38 ACM 150-38	150	38,1	30	9,5 x	4° / 2°	7
COL 200-38 TEL 200-38 ACM 200-38	200	38,1	30	12,7 x	3° / 1,5°	5
COL 300-38 TEL 300-38 ACM 300-30	300	38,1	30	19 x	2° / 1°	3,5
COL 300-57 TEL 300-57 ACM 300-57	300	57	50	19 x	2° / 1°	3,5
COL 500-57 TEL 500-57 ACM 500-57	500	57	50	31,5 x	1,2° / 0,6°	2
COL 1000-115 TEL 1000-115 ACM 1000-115	1000	115	100	64 x	0,6° / 0,3°	1

*First value for collimators and telescopes, second value for autocollimators







The product range shown in the table is also standardly available in modified/upgraded versions with following features:

2-axes eyepiece micrometer	MICRO
2-axes eyepiece digital micrometer	DIGI
Focusing Tube	F
Large Field	LF
Reticle changer	RC
Reticle and Filter changer	RC/FC

LARGE FIELD AUTOCOLLIMATORS

To meet customer requirements for testing optical instruments with large field of view, TRIOPTICS developed a new and unique line of autocollimators, collimators and telescopes providing a significant increase of field of view. Equipped with suitable reticles the Large Field Autocollimators give for the same focal length a field of view larger by 50-150% compared with the standard line.

TYPE	Focal length (mm)	Tube diameter (mm)	Free Aperture (mm)	Field of View/ Measuring Range	Resolution (arcsec)
ACM 300-57 LF	300	57	50	3°/1,5°	3,5
ACM 500-57 LF	500	57	50	1,8°/1,2°	2
ACM 1000-115 LF	1000	115	100	0,9°/0,5°	1

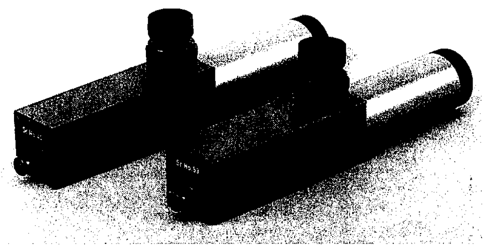
The angle resolution listed is related to the standard version of the instruments. Equipped with upgraded reading devices, the angular resolution can be significantly increased. An example for a selected focal length e.g. 500 mm shows the range of angular resolution obtainable with the same system:

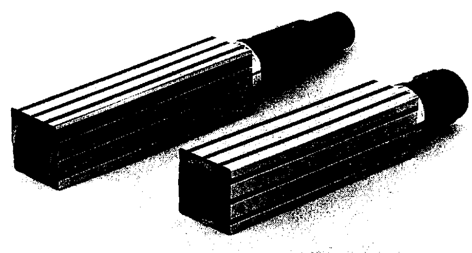
	Standard AC-Head	AC-Head Eyepiece Micrometer	AC-Head Digital Micrometer
Autocollimator ACM 500-57	2 arcsec	1 arcsec	0,2 arcsec

LED-AUTOCOLLIMATORS

The LED-Autocollimators are light, compact autocollimators made according MIL-Standards (high and low temperature, shocks, humidity etc). The LED-Illumination enables a practically unlimited life period.

TYPE	Focal length (mm)	Tube diameter (mm)	Free Aperture (mm)	FOV Measuring Range	Resolution (arcsec)
ACM140-40 LED	140	40	30	4°/2°	7





OPTITEST / SPHEROMETERS

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DIOPTER TELESCOPES

The Diopter Telescope or Dioptometer is a focusing telescope measuring the power of lenses in diopters. The results of the measurement can be read off on a graduated scale.

<table>
<tr><th>TYPE</th><th>Focal length (mm)</th><th>Field of View</th><th>Height H (mm)</th><th>Range (Diopter)</th><th>Scale (Diopter)</th></tr>
<tr><td>DPT -5/+5</td><td rowspan="4">40</td><td rowspan="4">13°</td><td>75-92</td><td>-5 to+5</td><td>0,2</td></tr>
<tr><td>DPT -3/+1</td><td>82-90</td><td>-3 to+1</td><td>0,1</td></tr>
<tr><td>DPT -1/+3</td><td>77-83</td><td>+3 to-1</td><td>0,1</td></tr>
<tr><td>DPT -5/+5</td><td>75-92</td><td>-5 to+5</td><td>0,1</td></tr>
</table>

SQUARE BODY TELESCOPES AND COLLIMATORS

The collimators and telescopes with square body have a cross reticle accurately aligned to the body flat surface i.e.mechanical axis of the instrument. The square body is used as a reference surface in solving alignment problems.

DYNAMETER

The Dynameter is used in optical testing for measurement of the exit pupil and magnification of various instruments.

BINOCULARS TESTING INSTRUMENTS

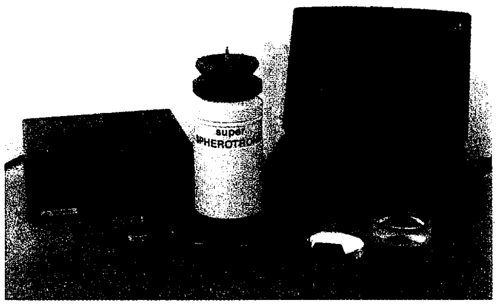
This instrument is used for testing the parallelism of optical axes of binoculars, image erection and the infinity setting. It includes two precisely aligned collimators, a double telescope mounted on a tilt table and an adjustable binoculars holder. All the components are conveniently mounted on a stand.

AUTOMATIC SPHEROMETERS

SUPER-SPHEROTRONIC for high-precision measurements

Super-Spherotronic is an automatic three ball contacting spherometer designed to meet the highest test plate calibration requirements. Being the most accurate instrument of our line of spherometers, Super-Spherotronic can measure the radius of curvature to an accuracy of 0.01%.

- To ensure that the highest available accuracy values of radius measurement are obtained, all Super-Spherotronic components have been optimized and perfected so that residual errors are negligible.

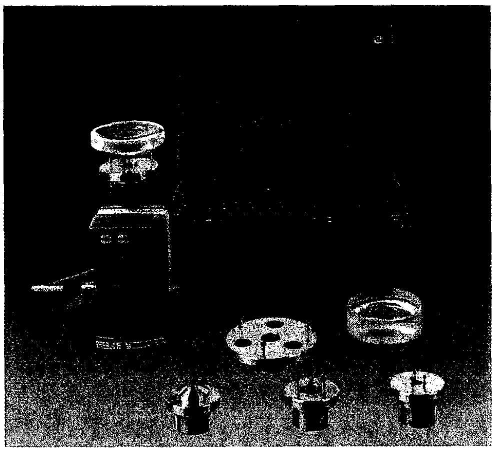


SUPER-SPHEROTRONIC

- The test plates used for calibration of the instrument are manufactured to high quality standards to an accuracy better than 1/10 wave for sphericity. The test plates are certified by NIST of USA, so that the accuracy of Super-Spherotronic is directly traceable to international standards.

SPHEROCOMPACT

SPHEROCOMAPACT is an extremely accurate and easy to use instrument designed for saggita measurement of both concave and convex surfaces.



- SPHEROCOMPACT is the first hand held spherometer with a high precision linear encoder which features bright digital readout, micron resolution and excellent absolute accuracy.
- The Spherocompact can be used either as a hand-held instrument to take measurements directly on the machine or as a stand-alone instrument in the laboratory.

APPLICATIONS

Due to their extreme accuracy and repeatability the TRIOPTICS spherometers are primarily used for calibration of master test plates, but also for any measuring problem requiring high precision evaluation of radius of curvature:

ADVANCED SOFTWARE

- The SPHEROWIN-Software package runs under Windows 95 (in German and English). The measurement results can be displayed in „mm" or „inch".
- Only this software package automatically recognizes when measuring convex and concave surfaces.
- It provides a statistic evaluation of the measurements including mean value and standard deviation.

PARAMETERS	SUPER-SPHEROTRONIC	SPHEROCOMPACT
Range of convex radii:	+ 3 mm to ∞	+ 2,5 mm to ∞
Range of concave radii:	- 6 mm to ∞	- 4 mm to ∞
Travel of linear encoder:	± 15 mm	± 15 mm
Diameter of part under test:	6 mm to 500 mm	5 mm...500 mm
Absolute accuracy of the linear encoder	± 0,2 µm	± 1 µm
Accuracy of measurement of radius of curvature	0,01 %	0,05 %
Ring diameters	7,5 mm, 20 mm, 38 mm, 60 mm, 90 mm, 120 mm	6 mm, 12,5 mm, 25 mm, 50 mm, 75 mm, 100 mm, 125 mm
Optional	150 mm, 225 mm	150mm, 225 mm

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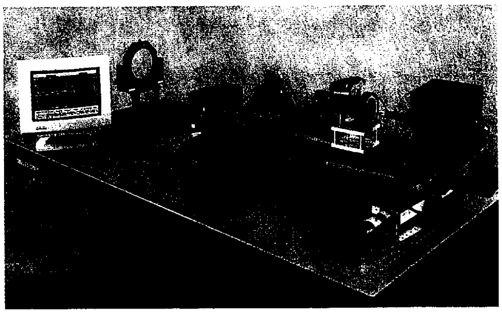
MTF-TEST STATIONS

DESCRIPTION

The computer-controlled MTF-Test Stations are designed to measure the optical performance of lenses and other image-forming systems.
Measurement capabilities include:

- Modulation Transfer Function (MTF)
- Phase Transfer Function (PTF)
- Effective Focal Length (EFL)
- Flange Focal Length (FFL)
- Field Curvature
- Distortion
- Relative Transmission and Vignetting
- Astigmatism
- Chromatic Aberration



Our MTF Test Systems offer exceptional levels of speed, accuracy and repeatability. The equipment is easy to use and can be configured for research or production testing.

Known as OPAL (Optical Performace Analyser for Lenses), the equipment range includes the following:

- OPAL Vector - visible testing using a linear photodiode array camera
- OPAL Matrix - visible testing using a 8-bit digital CCD video camera
- OPAL MatrixPlus - visible testing using a 10-bit digital CCD video camera
- OPAL IR - infra-red testing using a single element detector
- OPAL Video - testing visible or IR video camera from the video signal
- OPAL CamTest - testing digital still cameras using an edge target

TYPICAL SPECIFICATIONS

	Vector	Matrix	Infra red
MTF Accuracy	± 0.02		
MTF Repea-tabili-ty	± 0.01		
Spectral range	350-1100 nm	350-1100 nm	3-5 um and 8-12 um
Spatial Fre-quency Range	0-2000 c/mm	0-2000 c/mm	0-60 c/mm
Number of pixels	256 or 512	768 x 484	1
MTF mea-sure-ment time	50 m sec	100 m sec	2 secs
Focal length range	2-1000 mm		
Maximum aperture	300 mm		
Maximum off-axis angle	± 60 degrees		

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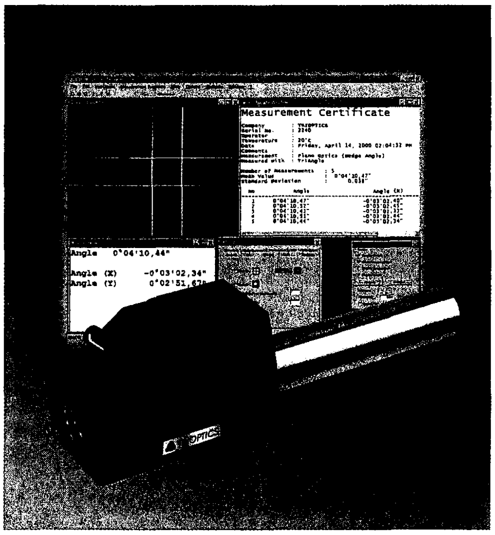
TriAngle
Electronic Autocollimator
measures angles along three axes

DESCRIPTION

TriAngle, the new Electronic Autocollimator series of Trioptics integrates a high resolution CCD-sensor and is compatible with all Trioptics objective tubes. The compatibility with objective tubes of different focal lengths leads to a variable measuring range and accuracy performance. In this way the TriAngle series responds optimally to different customer requirements and can cover a large range of applications.



The versatility of **TriAngle** is further enhanced by the modular design which allows fitting of different:

- reticles: bright or dark crosshair, pinhole, etc.
- illuminations: LED, laser diode, halogene lamp
- CCD-sensors: 1/3", 1/2" (Standard), 2/3"

TriAngle is designed for outstanding performance and flexibility. Depending on the focal length of the instrument, the standard measuring accuracy varies from 0.2 to 2 arcsec and the resolution is in the range of 0.01-0.1 arcsec. Higher performance is available on request.

FEATURES

- integrated HR CCD-sensor
- variable measuring range
- it measures optics and aligns mechanics

The extensive software package covers a multitude of applications: tilt and wedge angle, prisms and polygons angles, alignment of mechanical set ups, etc. Custom measuring procedures can be easily interfaced with the instrument software program.

MEASURING PITCH, YAW AND ROLL ANGLES

For the first time an Autocollimator can measure angles along three axes. A proprietary reflector design combined with a sofisticated software enable the measurement not only of the two classical tilt angles (pitch and yaw) but of the roll angle (rotation around autocollimator axis) as well.

PRODUCT RANGE

Code	Type	Resolution (arcsec)	Repeatability Std.Dev. (arcsec)	Accuracy (arcsec)	Description
3-103-061	TA 100-38	0.1	0.5"	2.5"	TA 100 - 38
3-103-062	TA 150-38			1.7"	Focal length (mm) Tube diameter (mm)
3-103-063	TA 200-38	0,01	0,2"	1.3"	The delivery kit includes:
3-103-064	TA 300-38			1.0"	• TriAngle-Autocollimator
3-103-065	TA 300-57			1.0"	• Frame Grabber
3-103-066	TA 500-57		0,1"	0.5"	• Software on disk
3-103-068	TA 1000-115		0,05"	0.2"	• Interface cables
3-103-069	TA 1000-140			0.2"	

AUTOMATIC CENTERING AND CEMENTING STATIONS

DESCRIPTION

The Automatic Centering and Cementing Stations integrate assemblies of TRIOPTICS OptiCentric-System for ultra-precison measurement of centration errors with automated cement dispensers and UV curing systems.

- The measurement of centration errors is PC controlled and can be carried out either in TRANSMISSION or in REFLECTION. To achieve this, the system incorporates electronic autocollimators with CCD-Cameras connected to PC-frame grabbers.

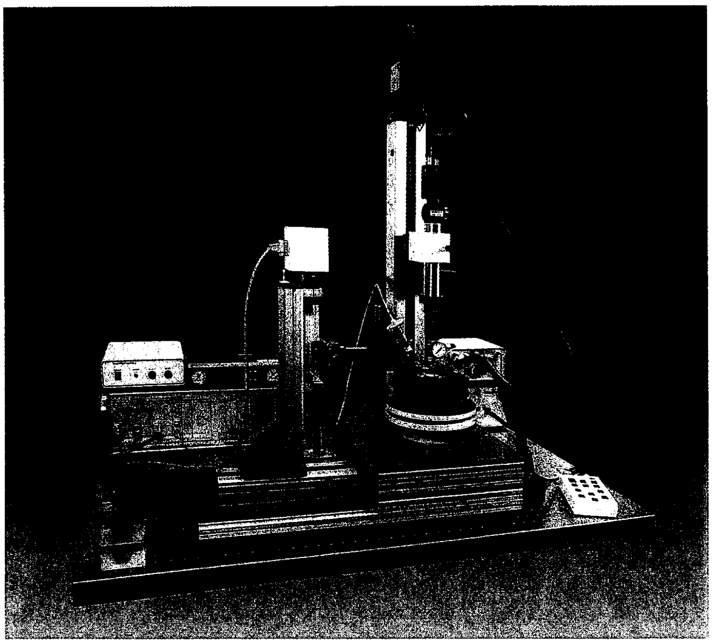
- The mechanical positioning assemblies include a range of high precision rotary holders with bell chucks and air bearing rotary tables. Alternatively a direct lens rotation device combined with vacuum lens holder is available.
- The dispenser is precisely positioned by means of a stepper motor stage. The dispensing time is coordinated with the lens rotation.

- Alignment of optics by means of a piezo-electric device with 0,1µm accuracy.

- The process of inspection, alignment, cementing and curing is completely automated. The different steps of the process are programmable.

SPECIFICATION

- Accuracy for centration measurement: 0.1 to 5 microns depending on the measuring configuration.
- Centering mode: transmission and reflection
- Sample diameter: 0.5 to 300 mm
- Measurement time: 1 sec
- Measurement wave length: centered on 546.1nm.



- Mechanical positioning:
  precision rotary holders
  lens rotation device with vacuum holder
- Dispenser and UV curing fully automated
- Operation systems for software: WINDOWS® and WINDOWS NT®
- Software language: free selectable in German and English.
- Angle units free selectable
- On site calibration procedure.

OPTICAL COMPONENTS AND MOUNTED OPTICS

OPTICAL COMPONENTS

The optical components offered by TRIOPTICS include a large variety of:

- lenses
- achromats
- prisms
- projection lenses
- spherical and flat mirrors
- off-axis paraboloids

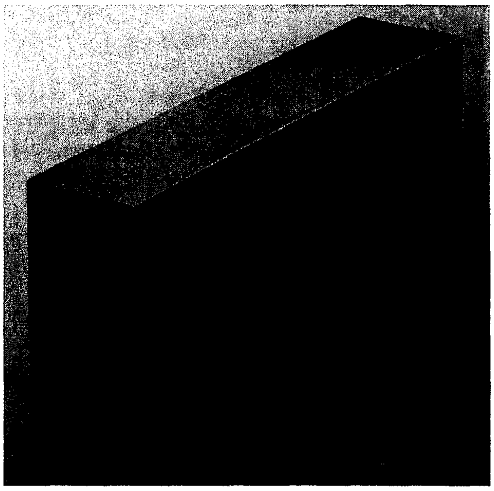
Dimensions up to 1300mm, surface accuracy up to $\lambda/20$. Materials include glass, ceramic, silica. These components are available in standard (catalog) sizes or (most of them) as O.E.M. products made to customer's own drawings.

MOUNTED OPTICS

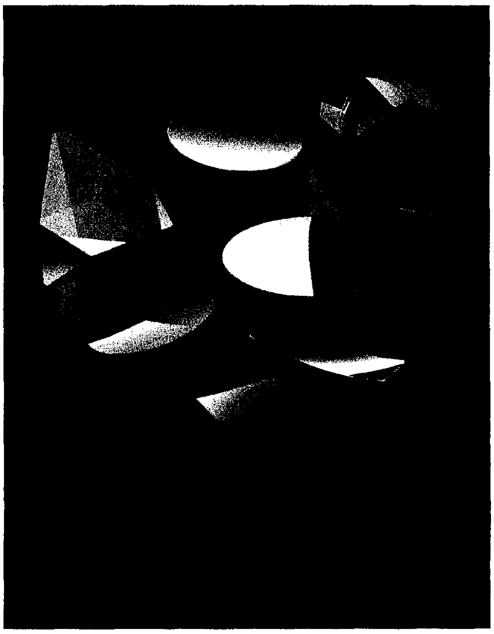
Any of the above mentioned optical components can be ordered mounted ready for use, either in standard or custom made mounts. In addition a standard range of :

- reflective laser beam expanders
- reflective tube collimators are available.

These products incorporates high precision off-axis mirrors coated from UV to IR.



BEAM EXPANDER



OPTICAL COMPONENTS

INTERNATIONAL AGENTS

TRIOPTICS

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To contact our international agents visit our Homepage at: **http://www.trioptics.com** For your convenience some of our representatives are listed below.

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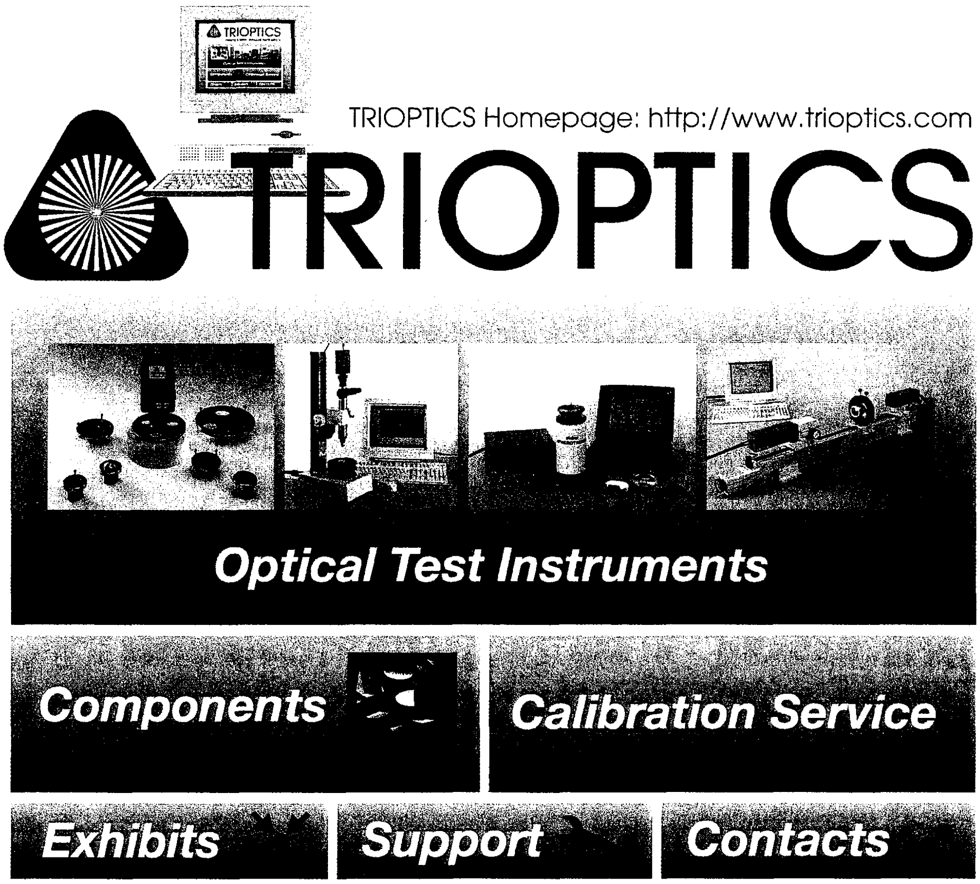
Visit our homepage for the newest information on the activities and products of our company!

TRIOPTICS´ Website provides online photos and product descriptions of our line of optical test equipment. Typical applications are detailed, helping the user to select the most suitable measuring instrument for his test problem. A direct link to our e-mail address allows fast, easy contact.

In addition the TRIOPTICS´homepage provides a listing of our international agents, information about the major exhibits and downloads of the newest software versions.



TRIOPTICS
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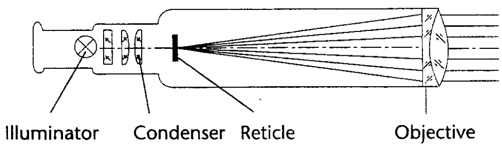
Structure – Operating principle

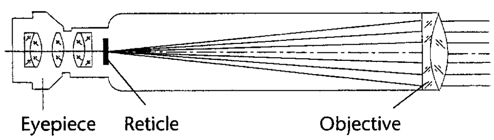
Brief Overview

Collimators, Telescopes and Autocollimators at a glance



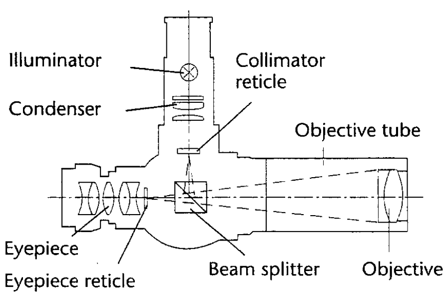
Collimator

A collimator projects a reticle to infinity. It may be used for testing instruments that require an object at infinity.



Telescope

A telescope has a reticle in the focal plane of the objective. It may be used in connection with a collimator for directional measurements.



Autocollimator

An autocollimator is a collimator and a telescope in one instrument. Autocollimators are high precision angle measurement instruments.

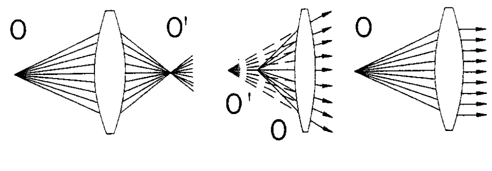
This table helps you to select the correct instruments

First find the measuring task in the left column below. Then choose a suitable method and instrument on the right.

Area of application	Measuring tasks	Method: Autocollimation	Instrument: Collimators	Visual Autocollimators	Electronic Autocollimators	Master Collimator	Dynameter	Diopter Telescopes	Universal Collimator	Telescopes
Field of Optics	Angle	■	◣	■	■	■			■	◥
	Back focal length	■	◣	■						◥
	Binoculars	■	◣	■						◥
	Flatness	■	◣	■						◥
	Optical power	■	◣	■		■		■		◥
	Parallelism	■	◣	■						◥
	Pyramidal error	■	◣	■	■					◥
	Radius of curvature	■		■						
	Roof angle	■		■						
	Sphericity	■		■						
	Telescopes									
	● Distance setting	■	■			■			■	
	● Exit pupil						■			
	● Field of view	■	■			■			■	
	● Graduation of reticle	■	■			■			■	
	● Magnification	■				■	■			
	● Resolution	■	■			■			■	
Machine construction	Dividing heads	■		■	■					
	Flatness of tables	■		■	■					
	Parallelism of guides	■		■	■					
	Rectangularity of guides	■		■	■					
	Straightness of guides	■		■	■					
	Angles	■		■	■					

Collimators, telescopes and autocollimators

Terms and definitions



a) b) c)

Optical imaging:

The transformation of a ray bundle from an object point O into another ray bundle that intersects at an image point O'.

Real image:

The real intersection point O' of a convergent ray bundle emerging from the optical system. (a)

Virtual image:

The apparent cross point O' of a divergent ray bundle. (b)
In the limit case O' lies at infinity. In this case there is no difference between real image and virtual image. (c)

Rear focal point F':

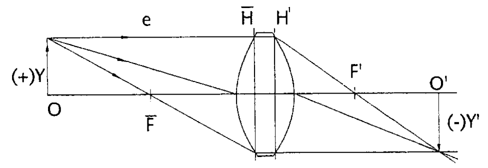
The image point located on the optical axis at which an optical system focuses an optical beam parallel to the axis.

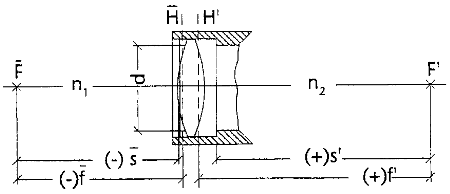
Front focal point $\bar{F}$:

Ray bundle from this object point located on the optical axis ($\bar{F}$) is transformed by the optical system into a beam parallel to the optical axis.

Front and rear principal point $\bar{H}$, H':

Points located on the optical axis which are the image of each other at equal height and direction:





Front and rear focal length $\bar{f}$ und f':

The distance between F and $\bar{H}$ and between F' and H'. Usually the refractive indices of the media in front of and behind the optical system n_1 and n_2 are equal: $n_1 = n_2 = 1$ (for air) and $\bar{f} = -f'$.

Clear aperture or aperture diaphragm (d)

for collimators, telescopes and autocollimators the clear aperture is determined by the free aperture of the objective mount.

Aperture ratio

is in this case d/f. This ratio is a measure of the image brightness.

Field angle 2 φ:

The angle between the principal rays originating from two marginal object points. Its size depends on the **field stop** and the **objective focal length.** The **free diameter of the retical** functions as a **field stop.**
The field angle is a measure of the dimension of the field of collimators, telescopes and autocollimators.

Field stop (2y')

is determined by the free diameter of the reticle. The field stop 2y' determines the ray bundle emerging from the object.

Telescope magnification V:

- Setting to infinity: $V = \frac{f_1}{f_2}$
- Setting to a finity distance: $V = \frac{f_1}{f_2}(1 + \frac{f_1}{e})$

f_1 = Objective focal length
f_2 = Eyepiece focal length

Terms and definitions

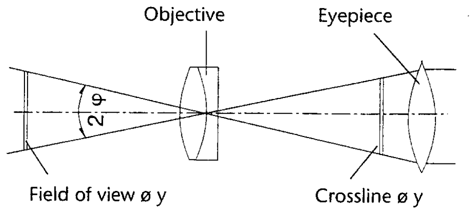
Field of view y:

Is the diameter of object field at the adjusted distance which is seen by an observer. Its size depends on:

$$y = y' \cdot \frac{f}{e - f}$$

- Field stop and the diameter of the reticle
- Objective focal length f
- Object distance e

The field of view gives the measure of field expansion of testing and reading telescopes set to a finite distance.



Refractive index n:

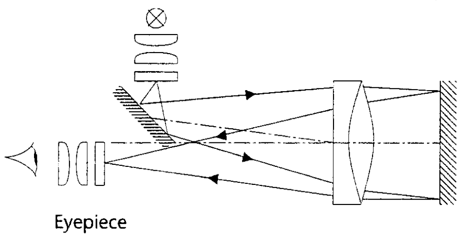
A material constant which determines the propagation of a light wave in the relevant medium. The absolute refractive index is defined as the ratio between the light velocity in the space and the medium:

$$n = \frac{c_{vak}}{c}$$

Refractive index is wavelengthdependent.

Optical path:

The change in the path of the light due to the difference between the speed of light in the medium compared to vacuum. It yields the product n·l with n as the refractive index and the length of the path. The optical path creates the physical conjunction between the vibrational frequency which yields from the wave nature of light and the density of the respective medium.

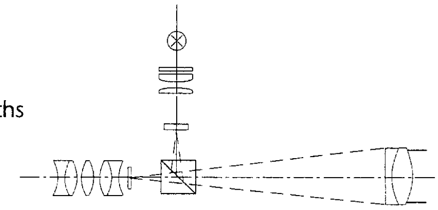


Geometrical beam splitting:

Geometrical splitting of the illumination and observation beam. Geometrical splitting yields a smaller field of view but higher brightness and a less scattered light. It is used for very small objects, e.g. prisms for endoscopes and miniature mirrors.

Physical beam splitting:

The physical beam splitting is commonly used with autocollimators. Both illumination – and observation paths use the full objective aperture.



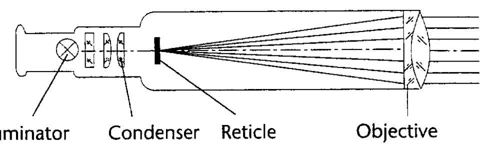
Structure and operating principle

Collimators

A collimator which projects the image of a reticle to infinity. Consequently, a bundle of parallel light emerges from the collimator. An image to the rear cannot arise.
The main components of a collimator are:

- **Tube with objective**
- **Adapter sleeve with reticle**
- **Illuminator**

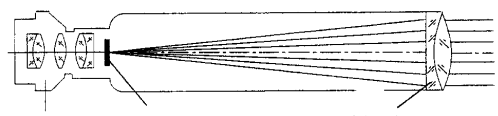
The reticle is located in the focal plane of the objective. The emerging beam is parallel.
A collimator with tube extension can be set to finite distances as well as infinity. In this case the beam is convergent or divergent and yields a real or virtual image of the reticle.



Telescopes

In industrial metrology telescopes are normally set to infinity or to a finite distance. Their main components are:

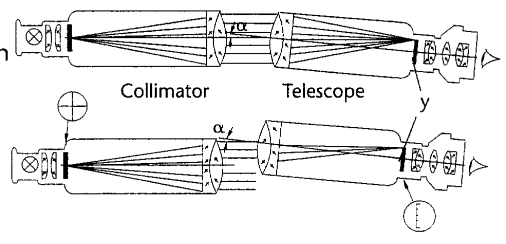
- **Tube with objective**
- **Adapter sleeve with reticle**
- **Eyepiece**



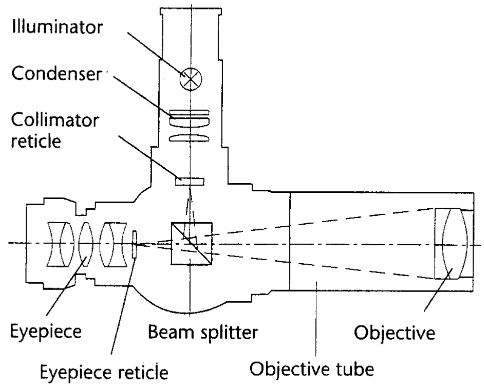
Collimator and telescope. A measuring combination for testing angular direction.

A collimator together with a telescope both set to infinity from an unit which measures the difference in angular direction of collimator to telescope. If the angle between the axes is α the crossline image of the collimator reticle is displaced by "y" in relation to the centre of the reticle in the eyepiece of the telescope.
A parallel displacement of either of the axes does not effect the angle measurement.

$$\alpha = \frac{Y}{\text{Focal length of the objective}}$$



Structure and operating principle



Autocollimators

A collimator combined with a telescope adjusted to infinity becomes an autocollimator.
An autocollimator consists of:

- **Tube with objective**
- **Autocollimation head with collimator- and eyepiece reticle**
- **Eyepiece**
- **Illuminator**

The autocollimation head serves as sleeve for collimator- and eyepiece reticles. The autocollimator head with eyepiece and illuminator forms a self-contained unit: autocollimation eyepiece.

Autocollimation eyepiece
\+ objective tube with objective

Autocollimator

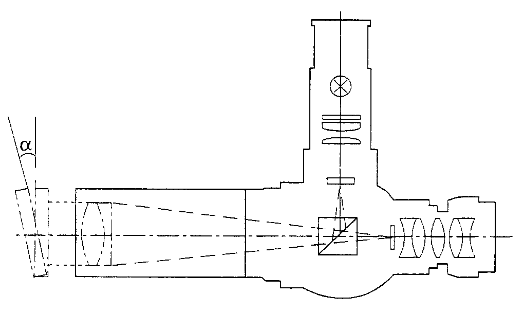
Autocollimation

Autocollimation: an optical procedure where a reticle image which is imaged back onto itself can be observed. Autocollimation is a sensitive procedure to detect small directional or tilt errors. It is generally used with an autocollimator set to infinity together with a plane mirror. To form an image in connection with spherical surfaces, the parallel beam path is converted into a concave or convex beam path via an additional objective, (achromat). In such set-ups autocollimation images emerge if the focal plane of the attachment achromat coincides with the centre of curvature of the surface.

Autocollimation is a procedure for directional testing. The accuracy of this measurement method is independant of the distance between Mirror/Autocollimator or Collimator/Telescope.

Autocollimation operating principle

The autocollimator projects the image of a reticle in a parallel beam of light (collimated light) onto a mirror which retroreflects the light bundle back into the autocollimator. That is how an autocollimation image is formed.
If the mirror is exactly perpendicular to the optical axis of the autocollimator the beam of light is reflected along the same path. When tilting the mirror the reflected beam enters into the objective at an angle.
Depending on the angle of the reflected light bundle the autocollimation image is displaced to a greater or lesser amount. The displacement of the autocollimation image in x- and y- direction provides a measure of the angular displacement of the mirror.



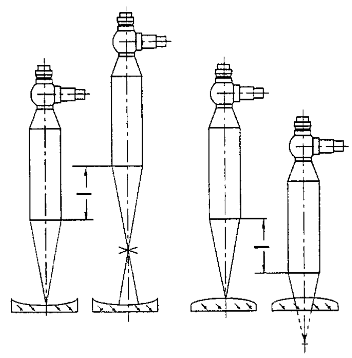
$\alpha = \frac{Y}{2f}$ f = focal length of the autocollimator objective

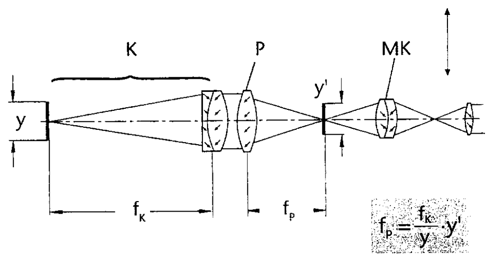
Applications in the optical industry

Determination of optical parameters

■ Radii of curvature of spherical surfaces

The autocollimator is adjusted to a finite distance. Autocollimation images occur at both the vertex and centre of curvature of the surface. The displacement "l" from one sharp setting to the other corresponds to the radius of curvature of the surface.





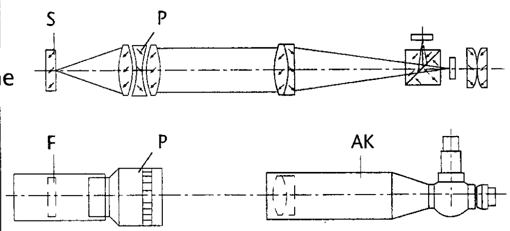
■ Focal and back focal length of positive and negative optical systems

Collimator K is set to infinity. A graduated scale y in the focal plane of the collimator is projected into the focal plane of the specimen P. The size of the projected image y' is measured with the microscope and the focal length read off from the scale.

Testing objectives

■ Testing the flange focal distance

If a plane mirror S or a film F is located exactly in the focal plane of the objective P the autocollimated image appears sharp and free from parallax.

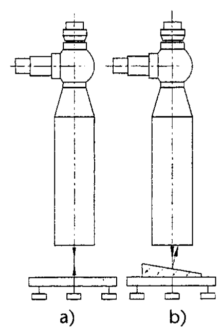


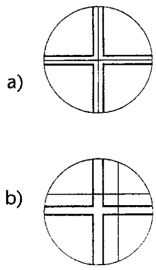
■ Testing the image quality

The collimator is adjusted to infinity. A resolution test is projected through the specimen (objective). The projected image is observed with an eyepiece.

■ Testing of distance setting

The autocollimator is set to the distance which is to be tested. In the image plane of the objective is placed a mirror or a film. If the specimen (objectives) is set to the corresponding distance the autocollimation image must appear sharp within the permissiple tolerance.





Testing optical components for angle errors

- ■ 90°-angles and pyramidal errors with glass prisms
- ■ Comparison of prisms with master prisms
- ■ Testing wedges and plane-parallel plates

Testing optical instruments

- ■ Image quality
- ■ Parallelism of the optical axes and image erection in binocular instruments
- ■ Distance setting

Collimators, telescopes and autocollimators

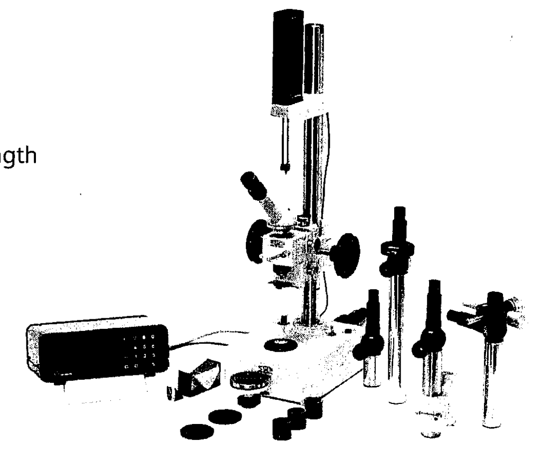
Applications in the optical industry

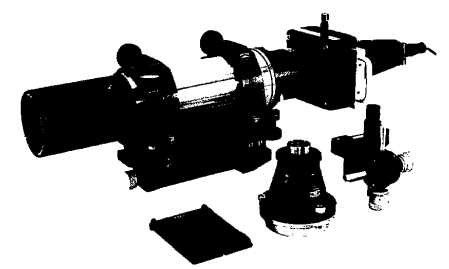
The variety of our collimators, telescopes and autocollimators allows the optimum arrangement to be set up according to the individual measurement task. For measurements occuring often we offer complete instruments:

Measuring Combination MELOS 500*

Versatile applications:

- Testing radii of curvature, focal and back focal length of optical components and systems.
- Testing prisms for angular errors
- Testing wedges and plane-parallel plates with autocollimator f = 140 and f = 300 mm





Universal Collimator*

to test optical instruments for:

- Resolution
- Distance setting
- Angular accuracy of reticles

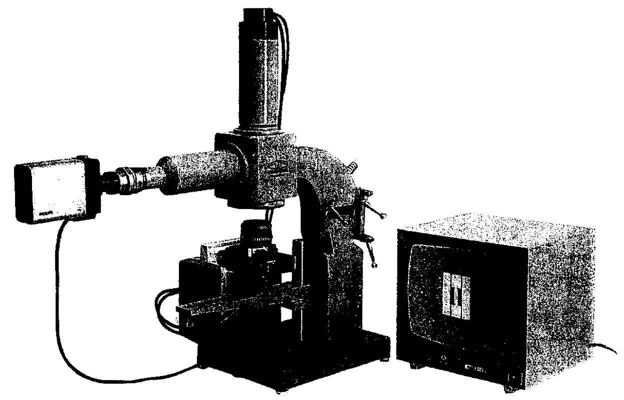
f = 500 mm, free aperture 90 mm, field of view 10°
with interchangeable reticle in cassette in system.
Extension to an autocollimator or telescope is possiple.

Camera Testing Instrument*

Setting and testing of:

- optical units
- multiple component systems (e.g. camera objectives, afocal systems)

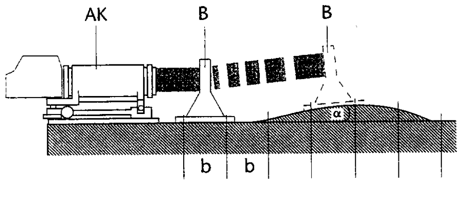
in the finite and infinite range.



* Ask for detailed literature.

Applications in the machine tool industry

Measuring the straightness



Determination of the differences in height by displacement of the base mirror in stages corresponding to base lenght in each case (distance between pins).The mirror is inclined at points which are not level.

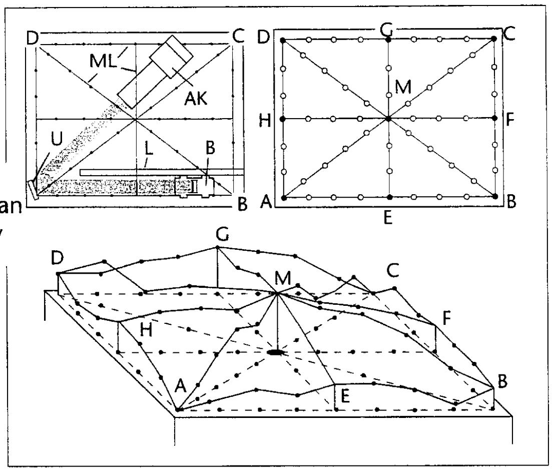
The difference in height Δ h ist: $\Delta h = \tan\alpha \times b$

α = Mirror inclination
b = Base lenght of the base mirror
AK = Autocollimator
B = Base mirror

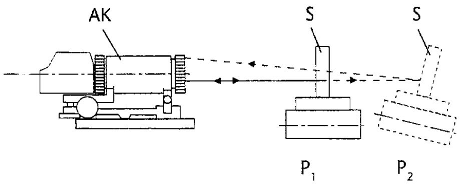
Measuring the flatness

The straightness of the 8 lines AC, BD, etc., is measured. Since each line has two common measuring points with other lines in other directions of measurement, the various contour lines can be linked together. Evaluation gives a topography of the measured surface.

L - Guide
B - Base mirror
U - Deflection mirror
AK - Autocollimator
ML - Measuring lines



Measurement of parallelism

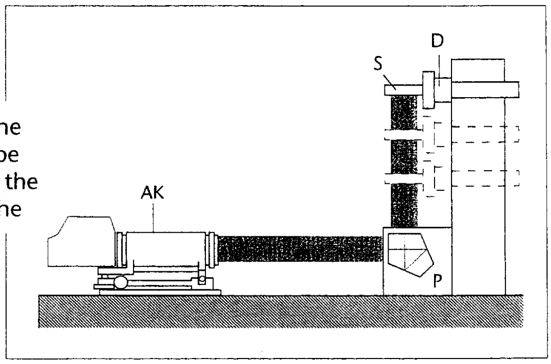


■ **Measuring of the parallelism of aligned shafts**

Mirror S is first positioned at test piece P_1 and then the autocollimator lined up with the mirror to fix the position of the autocollimation image. Subsequently the mirror S is positioned at test piece P_2 and the position of the autocollimation image noted. The displacement of the autocollimation image yields the deviation from the parellelism.

■ **Measurement of parallelism of adjacent or superimposed bore holes**

Mirror S is fixed to a mandrel D and is placed in the bore holes to be tested. A pentagon prism P can be used as the deviating mirror. The displacement of the autocollimation image yields the deviation from the parallelism.



Autocollimators

Applications in the machine tool industry

Quality assurance of machine tools

The new generation of electronic autocollimators* from Möller-Wedel offers access to new ways of assuring quality of machine tools, production facilities and machines of any type. Wherever highest angular accuracy is wanted:

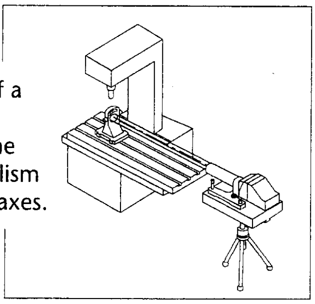
- In the production and assembly of machine.
- For inspection, service, calibration.
- For the continuous monitoring of production facilities.

This versatility enables rationalized quality assurance and forms a basis for an economical solution of problems.
Our electronic autocollimators measures without contact using a light beam, electronically controlled. Computer optimized optical systems and the most up to date microelectronics guarantees good quality and unique reliability. The technical features speak for themselves:

- Electronic sensing with CCD-lines
- Resolution: 0.05"
- System accuracy: ± 0.25"
- Measuring range: ±1000"
- Integrated microprocessor with standard software for typical applications
- RS 232 interfaces for computer and printer

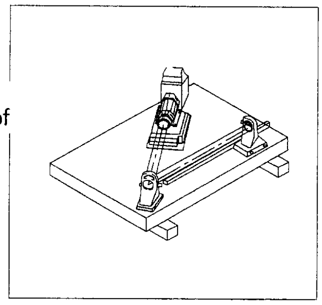
Straightness

The straightness of a machine bed, the angular slope of the slide or the parallelism between paths or axes.



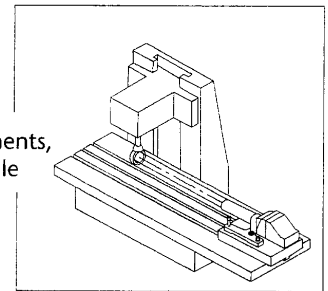
Flatness

The flatness of large plates and levelling of machine bases.



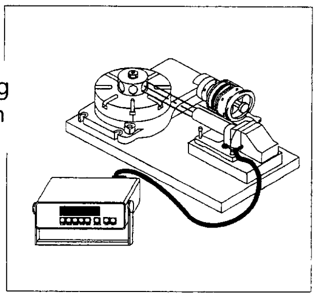
Right angle measurement

Between axes or machine components, or between spindle and slide travel.



Calibration

Calibration of dividing and rotary tables with highest precision.



* Please ask for detailed information

Subject to alterations

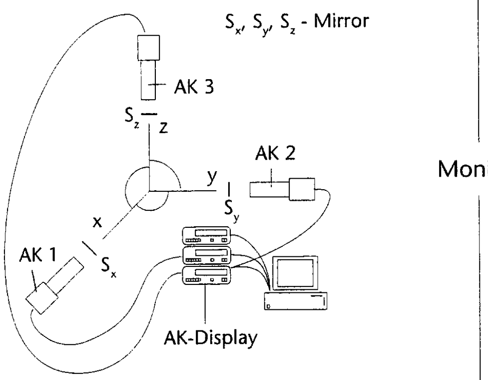
Autocollimators

Applications in the assembly line

Integration into automatic assembly lines

- Automatic monitoring of angular positions
- Compensation of drift phenomena with optical and mechanical set-ups.

With the availability of standard (RS 232 and IEEE) interfaces the electronic autocollimator* can be integrated into monitoring and assembly systems. A computer can compare the actual angle values of several autocollimators with the nominal values and compensate the deviations by suitable adjustment and control devices.



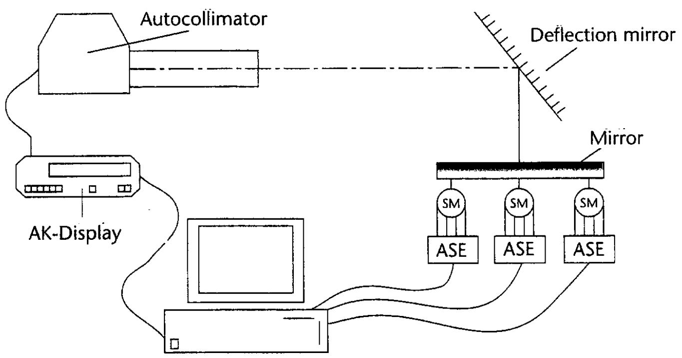
Monitoring the position of a multi-axis system

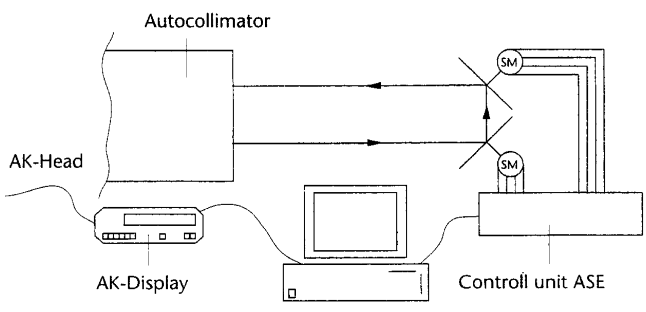
Automatic mirror adjusting during assembly

Example: Adjusting a mirror to the optical autocollimator axis, PC controlled

SM - Stepping motor

ASE - Control unit





Example: Adjustment of an optical set-up using an electronic autocollimator, PC controlled

SM - Stepping motor

AS - Control unit

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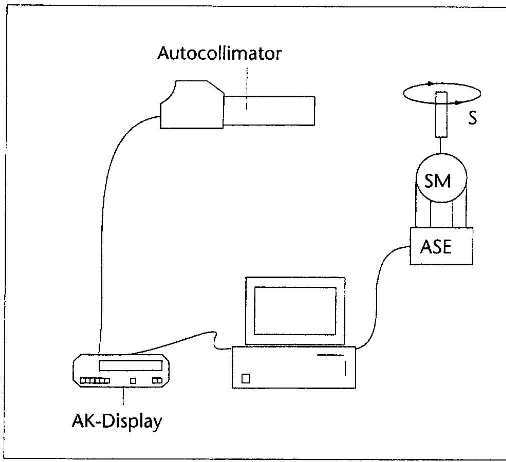
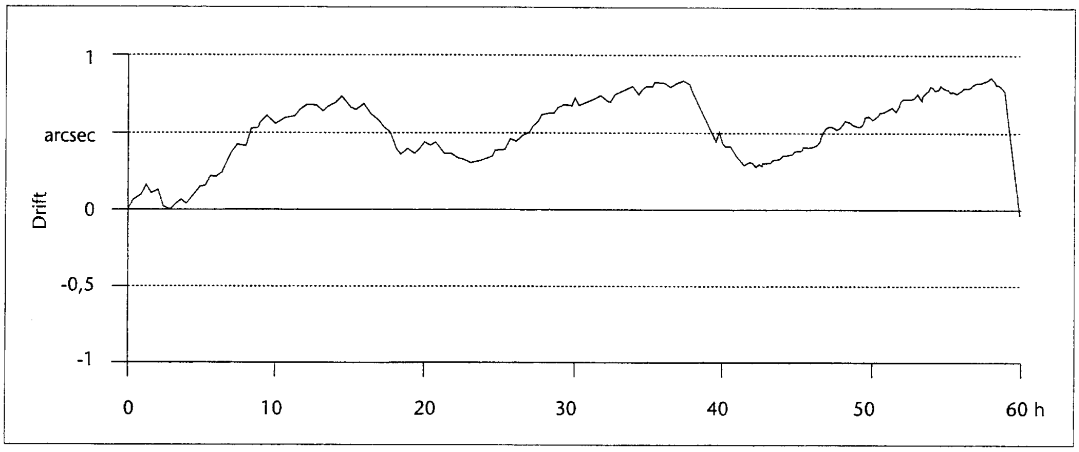
* Please ask fo detailed information

Applications in the laboratory



By connecting the control unit of the electronic autocollimator* to a computer it is possible to make long-term studies on the stability and drift properties of equipment to develope angle scanning units, etc.

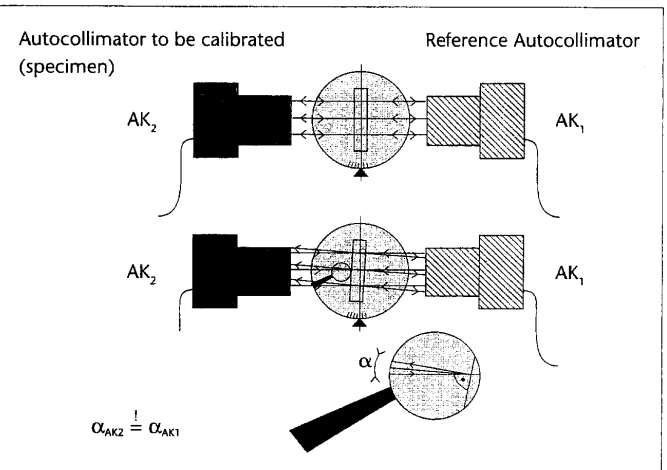
SM - Stepping motor
ASE - Control unit
S - Mirror



Long-term studies of the drift properties of a positioning set-up with hybrid-/stepping motor. The test arrangement consists of a plane mirror, an electronic autocollimator*, an IBM compatible computer and an output device.

Calibration of autocollimators

Both the reference- and autocollimator to be calibrated are aligned to a double-sided plane-parallel mirror on a precision rotary table. If the table is rotated by a small angle both the test and the reference autocollimators will show a change in angle. The difference in angle reading will be the error in the test instrument.



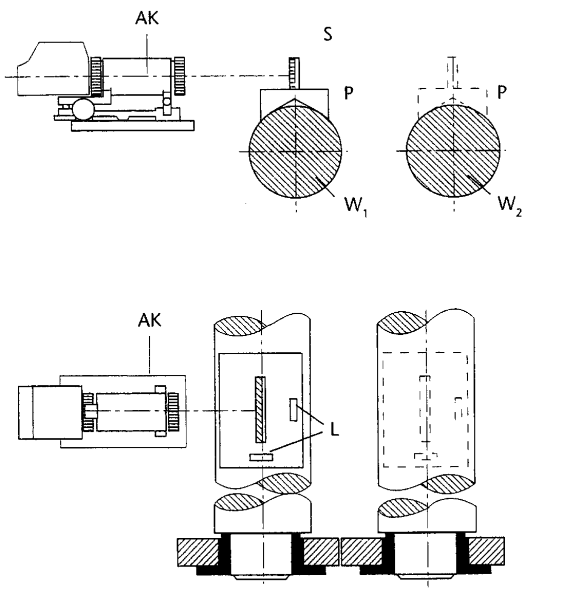
* Please ask fo detailed information

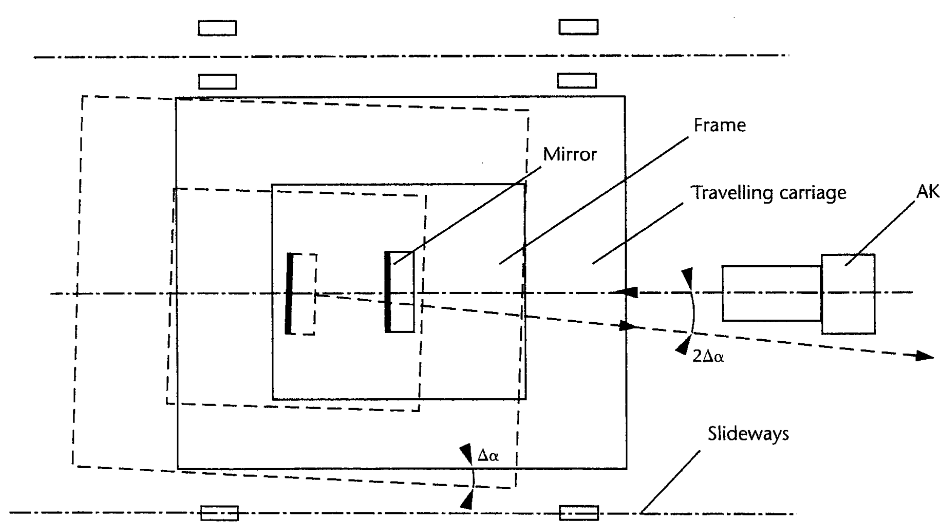
Applications in the printing and scanning technique

Measurement of parallelism of rollers

Mirror S is mounted on a V-block with two spirit levels (L) on the top surface. The V-block is placed on the first roller and levelled in longitudinal and transverse direction. The autocollimator is adjusted to the mirror S and then the block is transferred to the second roller which is then adjusted to the autocollimator so that the longitudinal level shows Zero and the eyepiece crossline stands symmetrically. After this both the axes are parallel to each other. Use of an electronic autocollimator shortens the measuring time and improves the accuracy.

AK - Autocollimator
W - Roller
S - Mirror
P - V-block
L - Level





Angle measurement in the structural components of photoscanners

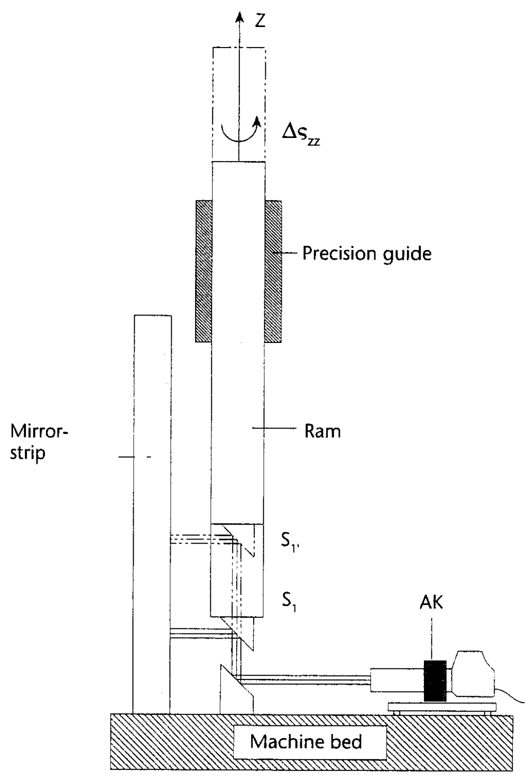
■ Examining errors in the slideways.

The scanner objective is replaced by a plane mirror and the autocollimator aligned to the mirror. As the mirror moves along the slideway the angle measured by the autocollimator will change if the rails are deformed or if there is a play in the bearings.

The autocollimator will measure angular changes in two axis as a function of time using suitable software.

Autocollimators

Applications in the 3D-metrology



Testing the ram movement on 3D-coordinate measuring machines

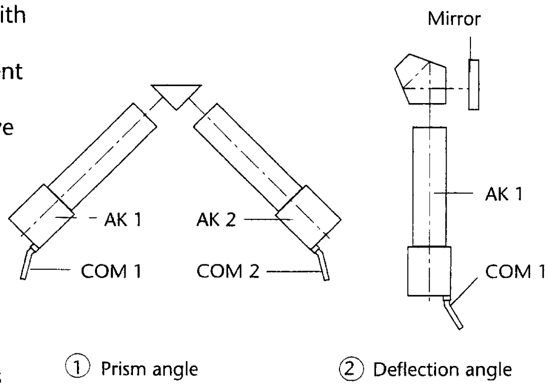
An electronic autocollimator can test the pitch and roll movement of a ram simply and precisely. The measuring accuracy depends on the flatness of the mirrors strip. MÖLLER-WEDEL produces mirror strips with a flatness better than 60 nm up to a length or approx. 600 mm. A Test Certificate can be supplied on request.

S_1 - Deflection prism
$S_{1'}$ - Position of the deflection prism after ram movement
A_K - Autocollimator
Δs_{zz} - Roll angle

Testing angles in production

- Measure facet angles of prismatic specimens with specular reflecting surfaces
- Measure deviation angles of optically transparent prisms

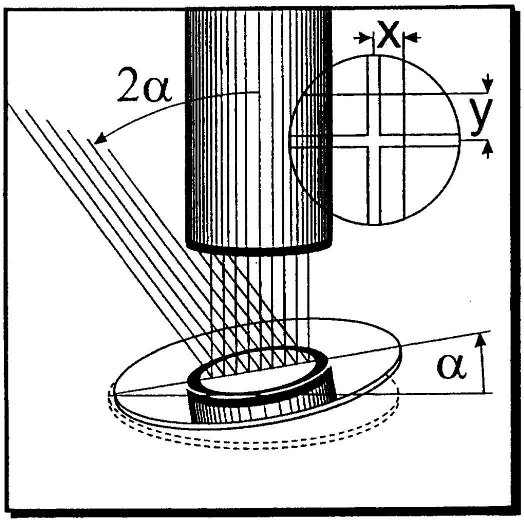
The electronic autocollimator* allows quick relative measurements of angles from specular reflecting surfaces and of deviation angles of transparent prisms in comparison with an etalon.
A software program is available to automate measurements. Futhermore the software permits the electronic autocollimator to be used in conjunction with the ISO 9000 system, thus linking measurements with quality assurance systems. MÖLLER-WEDEL offers complete systems including tested and certificated etalons.



AK - Electronic Autocollimator
COM - Interface

* Please ask fo detailed information

Examples for Applications of Collimators, Telescopes, Visual and Electronic Autocollimators



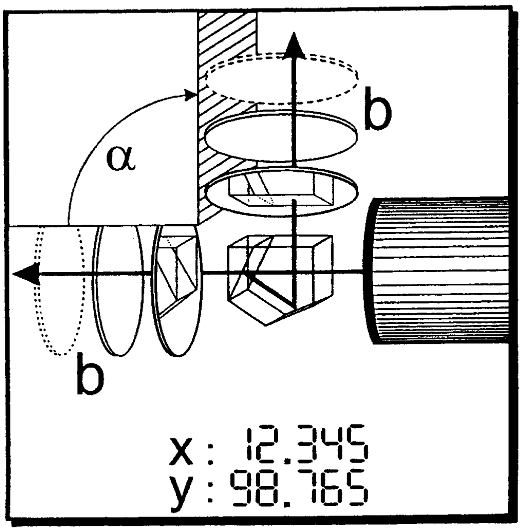


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Table of Content

1. Introduction

Autocollimators are high-precision instruments for measurement of angular settings. Principal field of application are calibration and measurement tasks in optical and mechanical engineering.

In the following a selection of examples from the wealth of applications is presented. The applications are roughly divided in two areas - optical and mechanical engineering. With this collection of examples we would like to give you an idea for the solution of your specific measurement problem.

The description of the measurement tasks is made for visual autocollimators. Nevertheless in most cases a computer aided evaluation by attaching a CCD-camera or with an electronic autocollimator ELCOMAT is possible, too. This kind of evaluation offers the advantage of enhanced accuracy with shorter even measurement time.

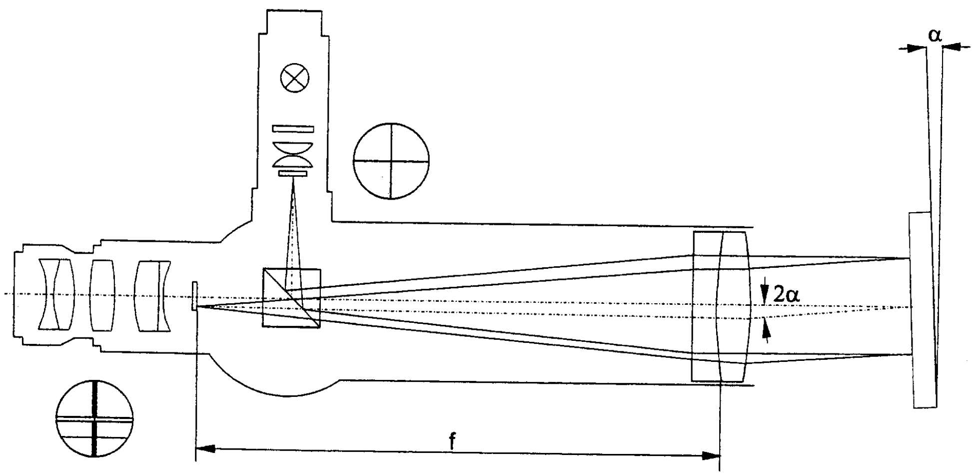
How autocollimation works

The autocollimator projects the image of a reticle marking in collimated beam path to infinity. A mirror in the optical path reflects the beam back into the autocollimator. The reflected beam generates the autocollimation image.

When the mirror is perpendicular to the optical axis, the beam is reflected into itself. When the mirror is tilted with an angle α, the incident ray enters the objective oblique. Depending the angle of the ray bundle to the optical axis, the autocollimation image is shifted from the centre.

The amount of shift in x- and y-direction is a measure for the tilt of the mirror:

$$\alpha = \frac{y}{2f}, \text{ f = focal length of the autocollimator.}$$



2. Applications in Optical Industry

Testing of Parallelism With Collimator And Telescope

Set-up:

- Collimator with reticle S115 (single crossline)
- Telescope with reticle S127 (double crossline) and double micrometer
- Index table or Goniometer
- Adjustable holders

First, read the angle between the optical axes of the telescope(collimator) and the front surface under test.

There are two autocollimation pictures: one from front surface and one from the rear surface.

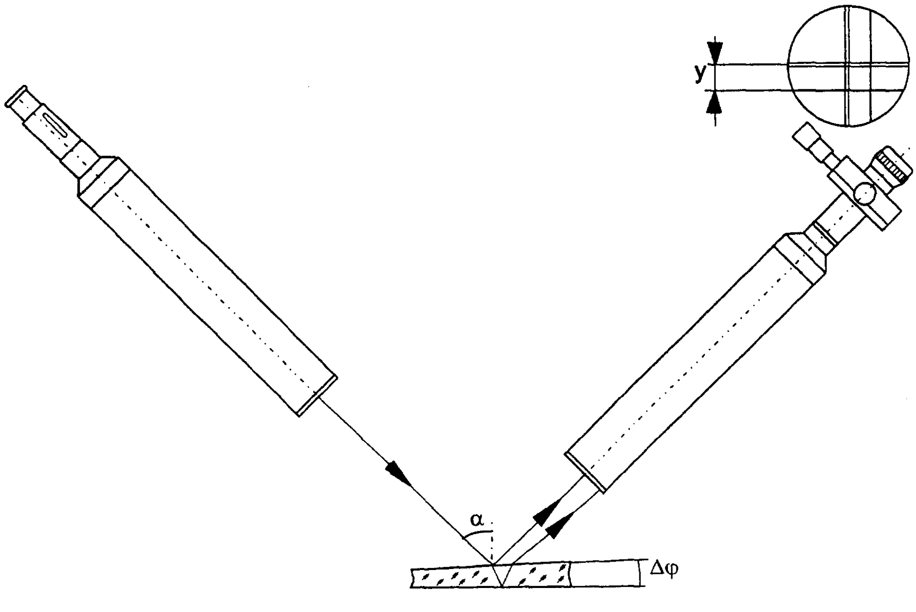
If both coincides the front and rear surface are parallel to each other.

If both pictures have a distance ΔY from each other the surfaces are not parallel. The distance ΔY is measured with the aid of the double micrometer:

$$\Delta\varphi = \frac{\Delta y \cos\alpha}{2f\sqrt{n^2 - \sin^2\alpha}}$$

where:

- $\Delta\varphi$: Wedge angle
- Δy: Distance of the autocollimation pictures
- n: Refractive index of the glass plate
- f: Focal length of the telescope
- α: Angle between the optical axes of the telescope (collimator) and the front surface of specimen to be tested.



Testing of Wedges and Plane Parallel Plates

Set-up:

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401 (reticle with graduation in mm)

and

- Supporting table with mirror surface
- Vertical stand
- Plan-parallel glass plate (mirror coated)

Adjust the supporting table with reflecting coating to the autocollimator. Put on the test specimen.

Turn the specimen in such a manner that the read out of the x-direction is zero. Read out the deviation Δy .

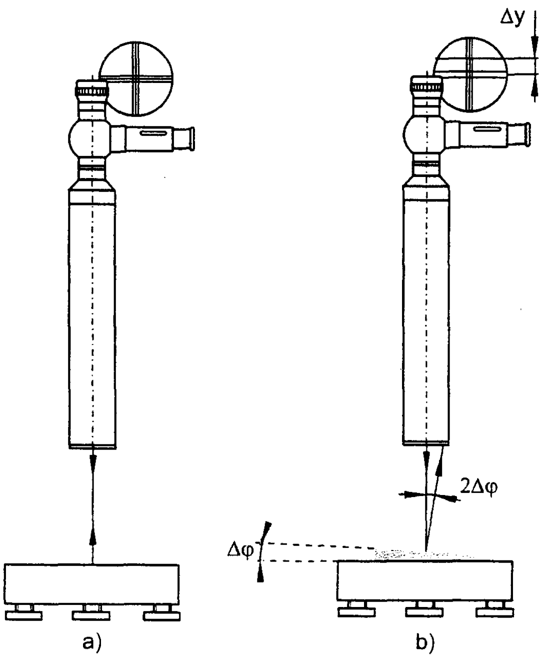
The deviation from plane parallelism is determined as per:

$$\Delta\varphi = \pm\frac{\Delta y}{2f}$$

where:

$\Delta\varphi$: Angle deviation of plane parallelism
Δy: Distance of the autocollimation image from its zero-position
f: Focal length of the autocollimator

In the case that the table is not mirror coated use a plane parallel mirror with known error and put this mirror on the supporting table. Then proceed as described under a) and b)



Testing of Transparent Wedges - Evaluation by Double Cross

Set-up:

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401...S431 (reticle with graduation)

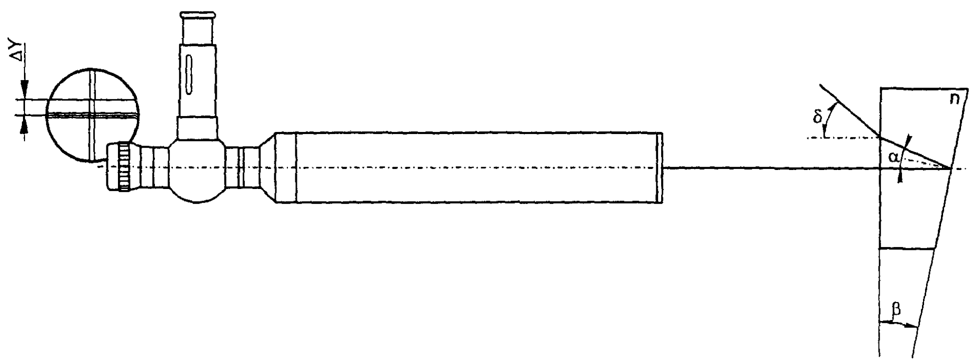
a) Adjust specimen to autocollimator in such a way, that one image of the collimator reticle is centred in the eyepiece reticle.

b) Rotate the specimen so that the angular deviation of the other reticle image is zero in x-direction. After reading the Δy respective $\Delta\varphi$, the angular deviation β can be calculated by ($\beta<5°$):

$$\beta = \pm \frac{\Delta y}{2nf} \quad \text{or} \quad \beta = \pm \frac{\Delta\varphi}{n}$$

where:

β:	Angular deviation from planarity
n:	refractive index of glass
$\Delta\varphi$, Δy:	Distance of the autocollimation image from its zero-position
f:	Focal length of the autocollimator



Testing of Transparent Wedges - Evaluation by Reference Mirror

Set-up:

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401...S431 (reticle with graduation)

and

- plane mirror

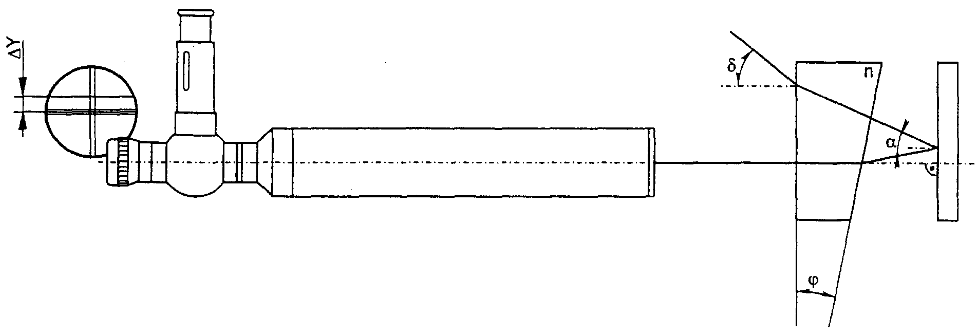
a) Adjust the reference mirror to the autocollimator in such a way, that the image of the collimator reticle (single cross) is in the centre of the eyepiece reticle.

b) Insert the specimen and adjust the angle to the optical axis of the autocollimator so, that it is smaller than approx. 5°. Rotate the specimen so that the angular deviation of the other reticle image is zero in x-direction. After reading the Δy respective $\Delta\varphi$, the angular deviation β can be calculated by ($\beta<5°$):

$$\beta = \pm\frac{\Delta y}{2(n-1)f} \quad \text{or} \quad \beta = \pm\frac{\Delta\varphi}{(n-1)}$$

where:

- β: Angular deviation from planarity
- n: refractive index of glass
- $\Delta\varphi$, Δy: Distance of the autocollimation image from its zero-position
- f: Focal length of the autocollimator



Testing of Transparent Wedges - Evaluation by Angular Deviation

Set-up:
- Telescope with double-micrometer, eyepiece reticle S127 (double crossline)

or
- Telescope with eyepiece reticle S304 (reticle with millimeter graduation)

and
- collimator with reticle S115 (single cross).

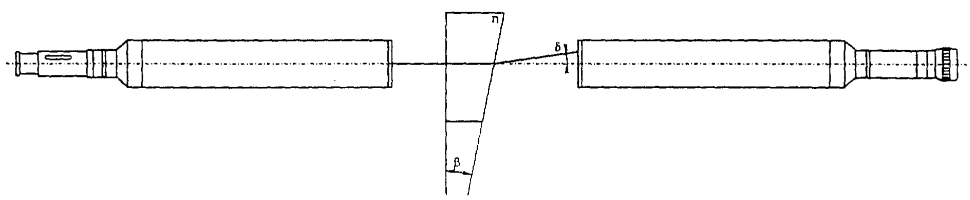
a) Adjust the telescope to the collimator in such a way, that the image of the collimator reticle (single cross) is in the centre of the telescope reticle.

b) Insert the specimen and adjust the angle to the optical axis of the autocollimator so, that it is smaller than approx. 5°. Rotate the specimen so that the angular deviation of the other reticle image is zero in x-direction. After reading the Δy respective $\Delta\varphi$, the angular deviation β can be calculated by ($\beta<5°$):

$$\beta = \pm\frac{\Delta y}{(n-1)f}$$

where:

β: Angular deviation from planarity
n: refractive index of glass
$\Delta\varphi$, Δy: Distance of the autocollimation image from its zero-position
f: Focal length of the autocollimator



Testing of the 90° angle of a 90°-Glass Prism

Set-up:

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401...S431 (reticle with graduation)

and

- Vertical stand (e.g. MELOS-measuring stand)

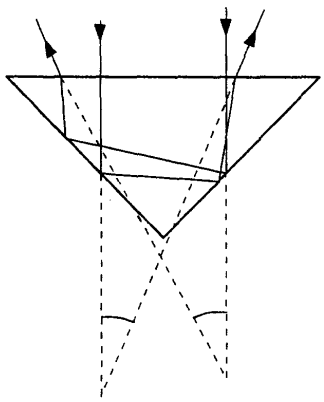
Adjust the autocollimator to the base of the 90°-prism. Three bright reticle images appear in the eyepiece. One from the base and two from the internal reflection in the prism. When rotating the prism around roof edge, the last two image remain in place. If the 90°-angle deviates from squareness ($\Delta\alpha$), the images from the internal reflection are separated by a distance $2\Delta x$ respect. $2\Delta\varphi$. When additionally the images are separated in height, the prism has also a pyramid error ($\Delta\beta$). The errors can be calculated according to:

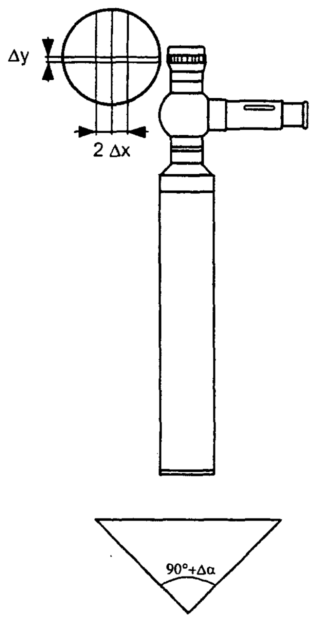
$$\Delta\alpha = \pm\frac{\Delta x}{2nf} \quad \text{or} \quad \Delta\alpha = \pm\frac{\Delta\varphi}{n}$$

$$\Delta\beta = \pm\frac{\Delta y}{2nf} \quad \text{or} \quad \Delta\beta = \pm\frac{\Delta\theta}{n}$$

where:

- $\Delta\alpha$: Error of the 90°-angle
- $\Delta\beta$: Pyramid error of the prism
- Δx, $\Delta\varphi$: Lateral separation of the reticles images from zero-position
- Δy, $\Delta\theta$: Vertical separation of the reticles images from zero-position
- f: focal length of the autocollimator





Testing 45° Angles of 90°-Glass Prism

Setup:
- Autocollimator with double micrometer, collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

or
- Autocollimator with collimator reticle S115 (single crossline) and eyepiece reticle S411...S431(angle graduation)

and
- Vertical holder (for example MELOS-Measuring stand)

Adjust the autocollimator to one of the short faces. There are existing two autocollimation images of both short faces which do only coincide if the 45° angles are exact.

Measure the distance between them, either with the aid of the eyepiece-double-micrometer or with a graduated eyepiece reticle.

$$\Delta\beta = \frac{\Delta x}{4nf} - \frac{\Delta\alpha}{2} \quad \text{or} \quad \Delta\beta = \frac{\Delta\varphi}{2n} - \frac{\Delta\alpha}{2}$$

where

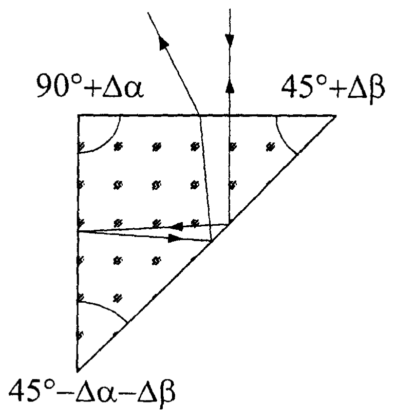
$\Delta\alpha$: Error of 90°-angle (to be measured in a separate step; see testing of the 90° angle of a 90°-glass prism)

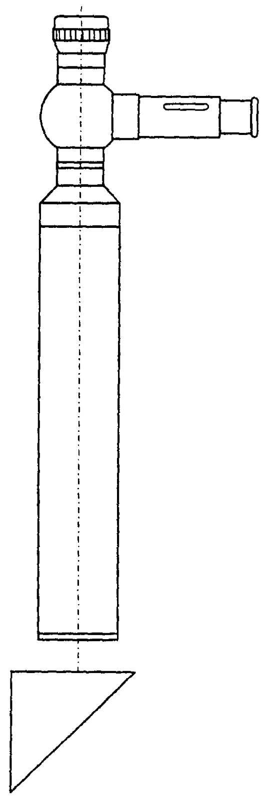
$\Delta\beta$: Error of 45°-angle

Δy: Distance of autocollimation images in the image plane

f: focal length of the autocollimation telescope

n: refraction index of the prism





Relative Measurement of Angular Error of Prism

Set-up:

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)
- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)
- Reference prism (master prism)
- Swivelling holder with tiltable supporting table
- Adjustable holder for second autocollimator

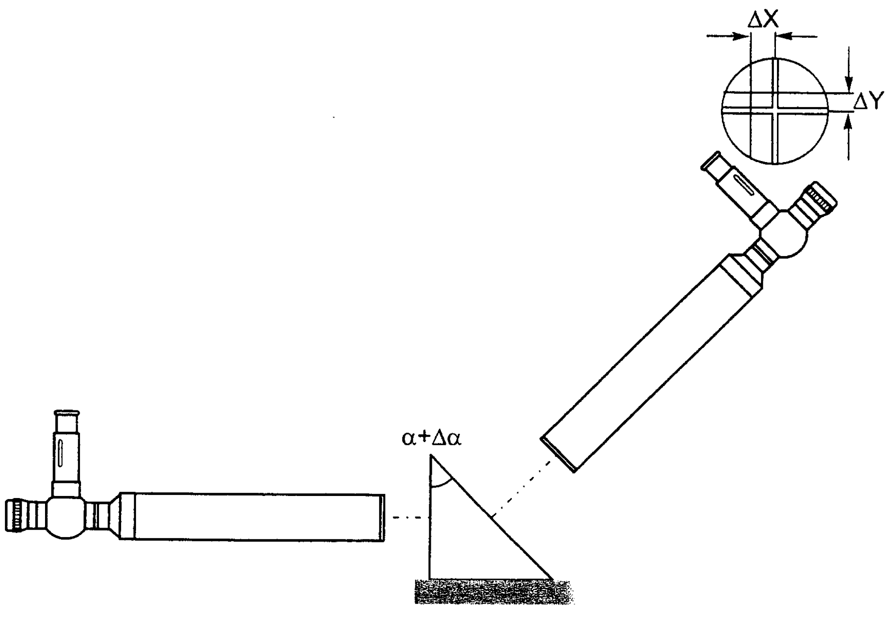
The reference prism is positioned on the tiltable supporting table. Both autocollimators are adjusted to respective surfaces of the prism. The fine adjustment of the prism to the first autocollimator is done with the adjustment screws of the supporting table. The fine adjustment of second autocollimator is made with the adjustment screws of the adjustable holder.

Now the reference prism is replaced with the test prism. The prism is adjusted to the first autocollimator with the supporting table. At the second autocollimator the distance of the reticle image in x- and y- direction are measured. The angular errors can be calculated according to:

$$\Delta\alpha = \pm\frac{\Delta y}{2f} \quad \text{and} \quad \Delta\beta = \pm\frac{\Delta x}{2f}$$

where:

$\Delta\alpha$: Angular deviation of the prism
$\Delta\beta$: Pyramid error of the prism
Δx: Lateral separation of the reticles images from zero-position
Δy: Vertical separation of the reticles images from zero-position
f: focal length of the autocollimator



Testing of Objectives

Set-up:

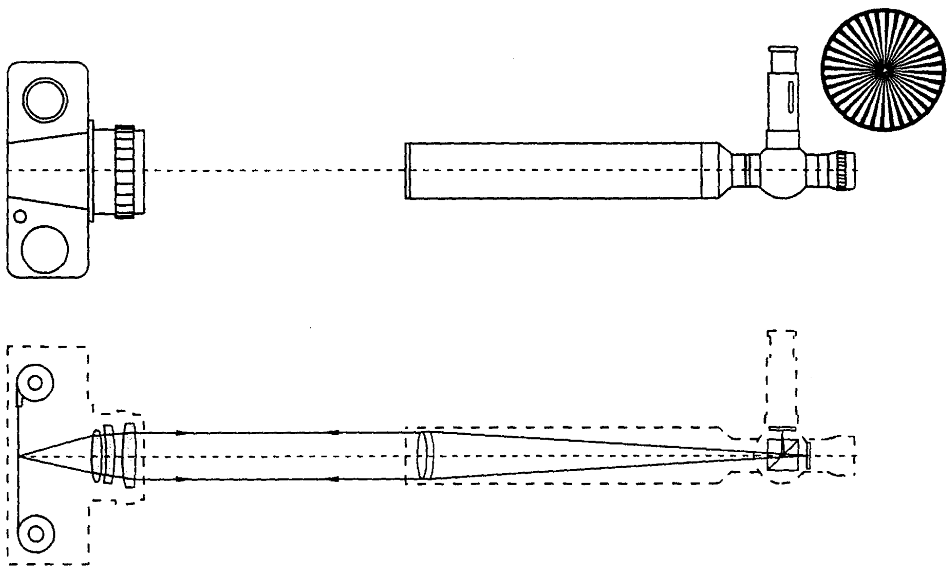
- Autocollimator with tube extension and collimator reticle S201, S202 (Siemensstern), S211 or S212 (resolution test) and eyepiece reticle S111
- plane mirror
- adjustable holder

Testing of the flange distance

Place a mirror or a film exactly in the image plane of the objective. If the autocollimation image appear sharply in the eyepiece, the position of the object is correct.

Testing of the distance setting

The autocollimator with tube extension is set to the distance to be tested (virtual setting). Place a mirror or a film exactly in the image plane of the objective. Set the objective by distance ring to the selected distance. If the distance setting is correct, the autocollimation picture is shown sharp.



Radius Measurement of Concave Spherical Surfaces

Set-up:

- Autocollimator with collimator reticle S201 or S202 (Siemens star);
- Attachment achromat (f = 50 / D16 to f = 500 / D50 depending on the radius to be measured.)
  Please note that f > r
- Measuring slide with length measuring system or MELOS stand

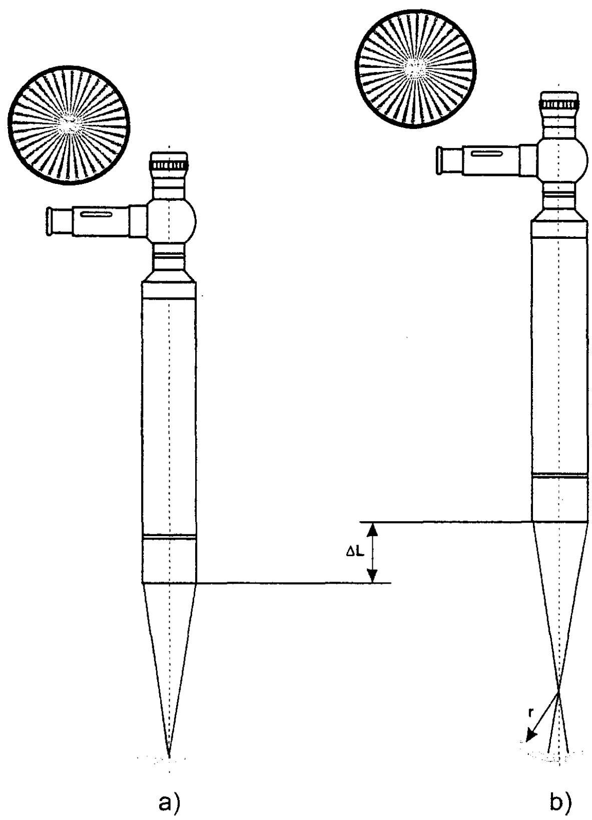
The attachment achromat converts the parallel beam to divergent or convergent beam (finite setting). If the autocollimator is focused to the vertex of the surface an autocollimation image occurs. The second autocollimation image occurs when the focal point of the attachment achromat coincidences with the center of curvature of the surface. The translation range to move the autocollimator from one picture to the next corresponds to the radius. When measuring transparent lenses additionally pictures form the back surface occur. That has to be taken in mind when selecting the corresponding pictures for radius measurement.

The measurement is done as follows:

a) Move the autocollimator along the translation slide until a sharp picture occurs (Siemens star sharp). Index the position.

b) Move the autocollimator to the next position until the picture is sharp. Index the second position. The difference of both index positions is the radius:

$$r = \Delta L$$



Radius Measurement of Convex Spherical Surfaces

Set-up:

- Autocollimator with collimator reticle S201 or S202 (Siemens star);
- Attachment achromat (f = 50 / D16 to f = 500 / D50 depending on the radius to be measured.)
- Measuring slide with length measuring system or MELOS stand

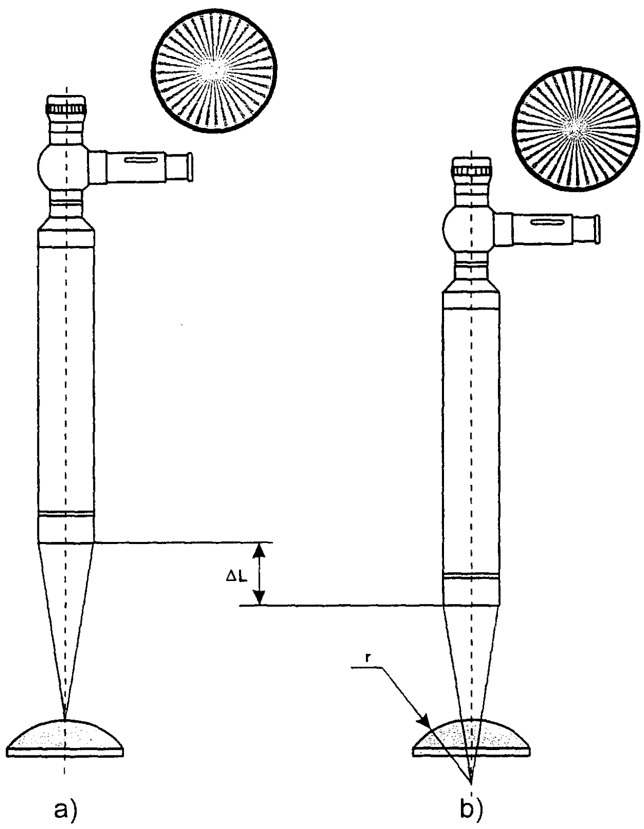
The attachment achromat converts the parallel beam to divergent or convergent beam (finite setting). If the autocollimator is focused to the vertex of the surface an autocollimation image occurs. The second autocollimation image occurs when the focal point of the attachment achromat coincidences with the centre of curvature of the surface. The translation distance to move the autocollimator from one image to the other corresponds to the radius. When measuring transparent lenses additionally images from the back surface can occur. That has to be kept in mind when selecting the corresponding images for radius measurement.

The measurement is done as follows:

a) Move the autocollimator along the translation slide until a sharp image occurs (Siemens star sharp). Index the position.

b) Move the autocollimator to the next position until the image is sharp. Index the second position. The difference of both index positions is the radius.

$$r = \Delta L$$



Flatness Testing of Reflecting Surfaces

Set-up:

- Collimator with collimator reticle S201 or S202 (Siemens star)
- Telescope with tube extension and eyepiece reticle S115 (single crossline)

By using the tube extension the distance between the objective and the reticles increases or decreases. In this case the telescope is set to a virtual or real object. The telescope head can be displaced by measurable values in both directions from zero position.

a) If the Siemens star is sharp in Zero position of tube extension the surface is flat.

b) If the Siemens star is sharp only after displacement of the telescope head through, the surface is spherical.

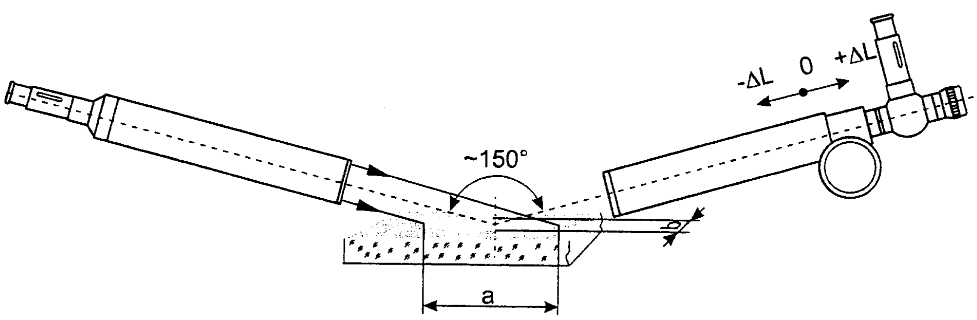
c) If the Siemens star has a different sharpness within the single test-directions the surface is irregularly curved. The different directions are to be adjusted sharply one after the other.

The deviation from flatness (radius) is determined from the equation:

$$r = \frac{2f^2a}{\Delta L \cdot b}$$

where

- r: Radius of curvature of the surface
- f: Focal length of the autocollimator
- a: Linear extension of the projected light bundle on the surface
- b: Width extension of the projected light bundle on the surface
- ΔL: Displacement of the telescope head (tube extension)



Control of Wedges and Plane Parallel Plates

Set-up:

- Autocollimator with collimator reticle S115 and eyepiece reticle S127

and

- Autocollimator with double micrometer, collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S111 (single crossline) and eyepiece reticle S411...S431 (reticle with angle graduation)

and

- Plane parallel plate or reference wedge
- Tiltable table

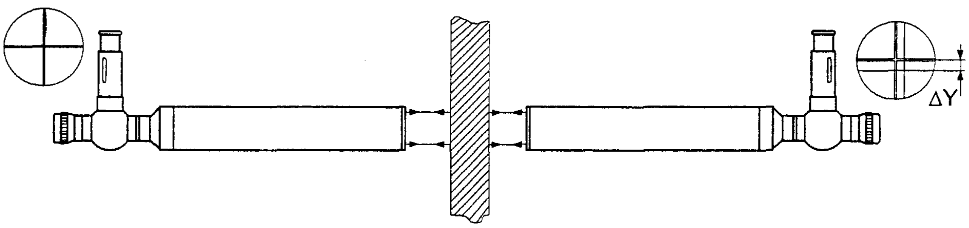
Both surfaces of the specimen should be flat and polished. Adjust both autocollimators with the help of the plane parallel plate or reference wedge. Insert the specimen and tilt it in such a way, that the single crossline is centred in the double crossline of the first autocollimator. Rotate the specimen around the optical axis, until x-axis reading in the second autocollimator is zero.

Read out the displacement of the autocollimation image of the second autocollimator by means of the double micrometer or the graduated reticle. The angle error calculates for use of micrometer as per:

$$\Delta\varphi = \pm\frac{\Delta y}{2f}$$

where

$\Delta\varphi$: Angle error of plan-parallelism (wedge)
Δy: Offset of the autocollimation image
f: Focal length of the autocollimator



3. Applications in Mechanical Engineering

Adjustment of Two Surfaces Parallel to Each Other

Setup:

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S401 (reticle with mm-graduation)

or

- ELCOMAT

and

- Vertical stand
- Plane parallel mirror

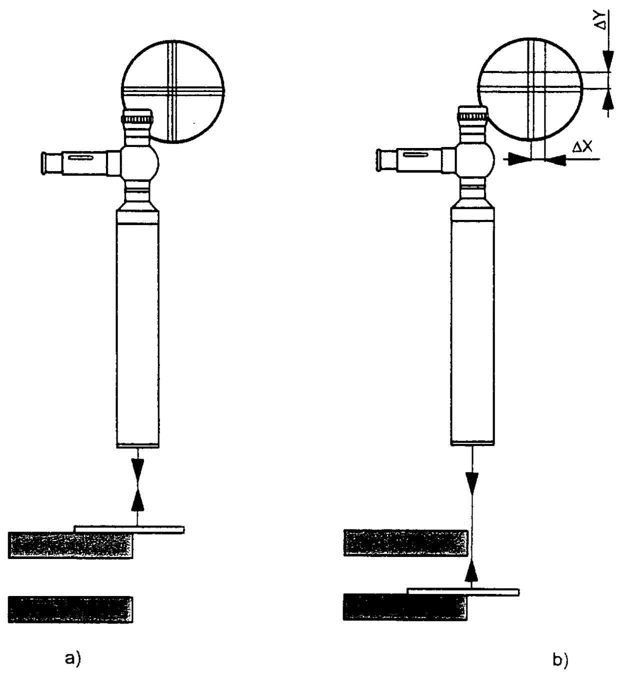
a) Put the mirror on one of the planes. Adjust the autocollimator in such a way, that the autocollimation image is in zero-position.

b) Put the mirror on the second plane and adjust the latter to the autocollimator. For determination of deviation from parallelism do not adjust the latter but readout Δx and Δy. The angular deviation the angle from parallelism can be calculated from:

$$\alpha = \frac{\Delta x}{2f} \quad \text{or} \quad \beta = \frac{\Delta y}{2f}$$

where

α:	Angle between surfaces in X-direction
β:	Angle between surfaces in Y-direction
Δx, Δy:	Distance of the autocollimation images from their zero-position
f:	focal length of the autocollimator



Adjustment of Two Surfaces Mutually Perpendicular

Setup:

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)
- or
- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S411...S431 (reticle with line- and grad graduation)
- or
- ELCOMAT

and

- 90°-prism
- Pentagon prism
- Adjustable holder

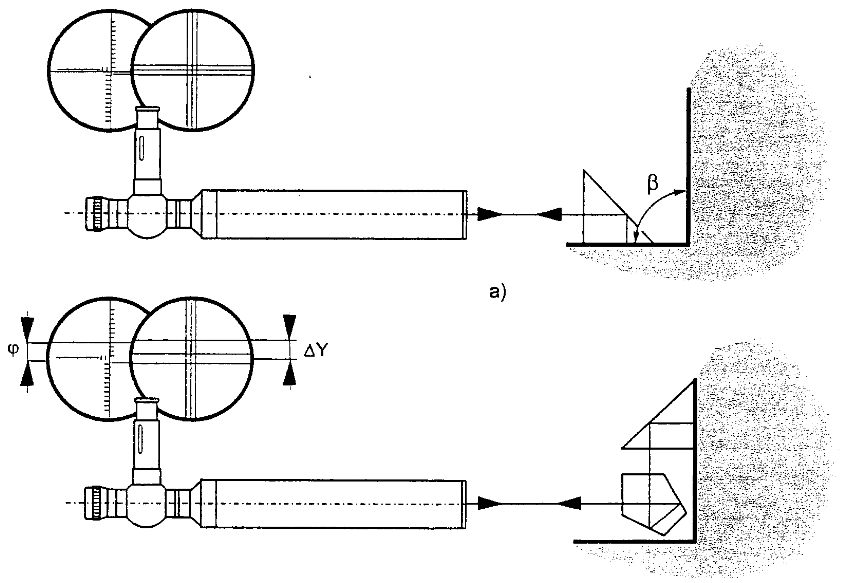
Set the 90°-prism on one of the surfaces to be tested. Adjust the autocollimation telescope by means of the prism to a plane.

After alignment of the autocollimator set the prism to the second surface to be tested. Use a pentagon prism to deflect the light bundle exactly by 90°. Read out Δy or $\Delta\varphi$ to determinate the angle between the both surfaces as per:

$$\boxed{\beta = 90° + \frac{\Delta y}{2f}} \quad \text{or} \quad \boxed{\beta = 90° + \Delta\varphi}$$

where

- Δy, $\Delta\varphi$: Distance of the autocollimation image from its zero-position
- β: Angle between surfaces
- f: Focal length of the autocollimator



b)

Parallel Setting of Rolls

Set-up:

- Autocollimator with collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

or

- ELCOMAT

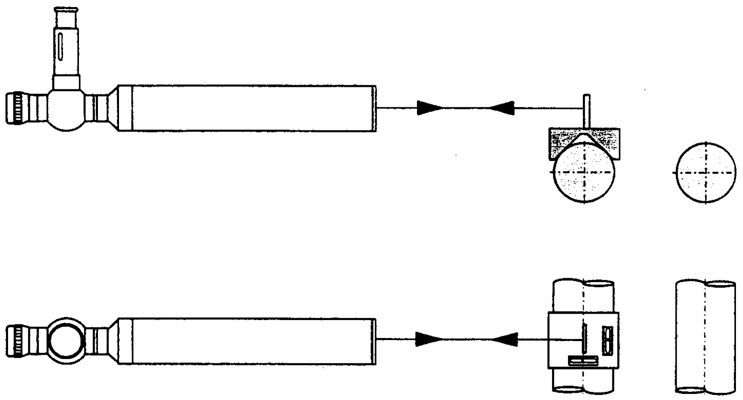
and

- Prism with flat mirror and cross-level

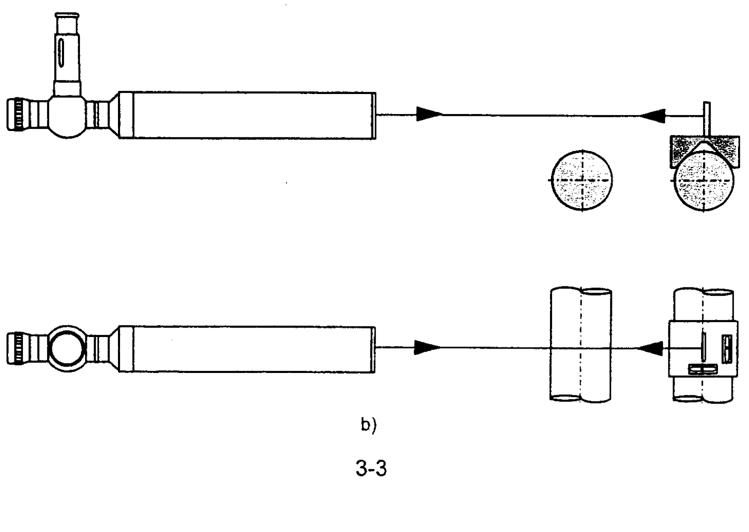
a) Adjust the prism with the reflecting mirror at the first roll to the cross-level; put the longitudinal-level by means of a corresponding set-screw at the zero position. Adjust autocollimation telescope to the mirror so that the reflection graticule is in the centre of the double graticule.

b) Put the mirror on the second roll and turn it to the cross-level. Align the rolls so that the longitudinal level is at zero and that the reflection graticule is centred in x-direction again in the eyepiece graticule. Now both rolls are parallel.

c) In the same way with unchanged position of the autocollimator additional rolls can be adjusted, too.



a)



b)

Pitch and Yaw Measurement of Slides

Set-up:

- Autocollimator with collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline) and eyepiece double micrometer

or

- Autocollimator with collimator reticle S115 (single crossline), eyepiece reticle S411...S431 (reticle with angle graduation) or S436...S445 (reticle with line and grad graduation)

or

- ELCOMAT

and

- Adjustable holder
- Base mirror
- Tripod

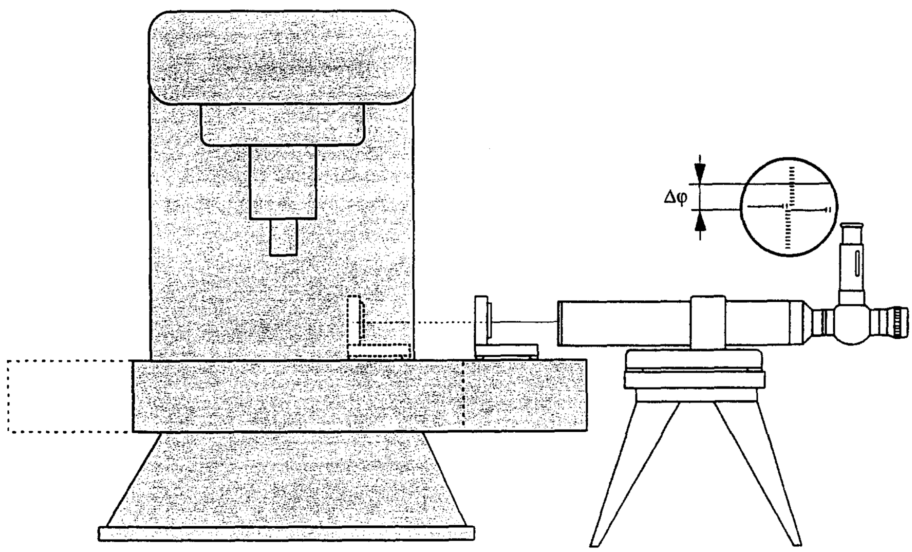
A plane mirror (base mirror or mirror with magnetic clamp) is fixed to the table. The autocollimator is aligned to the mirror. The table is moved in steps or continuously. If there is a pitch or yaw error the autocollimation image moves. The extrema of the image movement are registered and the angle error determinates as per:

$$\Delta\varphi = \frac{y_{max} - y_{min}}{2f} \quad \text{or} \quad \Delta\varphi = \varphi_{max} - \varphi_{min}$$

where

y_{min}, φ_{min}: Minimum value,
y_{max}, φ_{max}: Maximum value,
f: Focal length of the autocollimator

With ELCOMAT 2000 or ELCOMAT vario the measurement is more precisely and the measurement time decreases rapidly.



Straightness Measurement

Set-up:
- Autocollimator with double micrometer, collimator reticle S115 (cross line) and eyepiece reticle S127 (double cross line)

or
- Autocollimator with collimator reticle S115 (cross line) and eyepiece reticle S411...S445 (reticle with angle graduation)

or
- ELCOMAT

and
- Base mirror
- Adjustable holder

Set mirror on sled. Adjust autocollimator to the mirror. Displace sled and observe the autocollimation picture. Each tilting of the mirror in the guiding direction and each turning effects a deviation of the autocollimation picture from the zero-position. A tilting vertical to the guide can be tested by a rectangular prism instead of a mirror.

Move the mirror by the base length of the mirror (100 mm or 50 mm) and read out each angle difference $\Delta\varphi$ to the previously determined angle.

$$\boxed{\Delta\varphi = \pm\frac{\Delta y}{2f}}$$

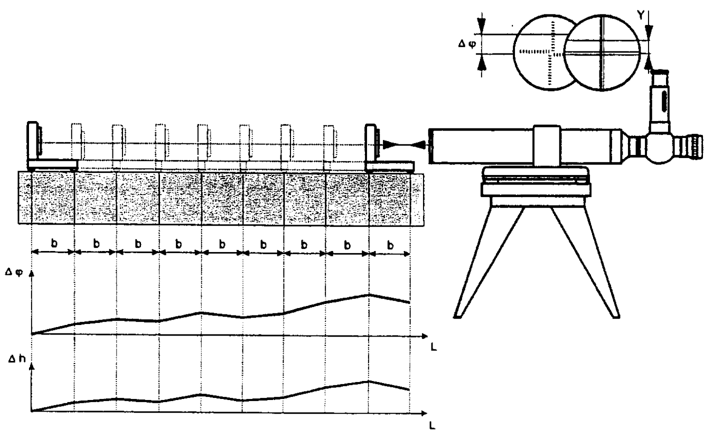
where
Δy: Distance of the autocollimation image from the previous position (zero-position)
f: Focal length of the autocollimator

The height difference from the mirror position to the previous position is than:

$$\boxed{\Delta h = b \cdot \tan\Delta\varphi}$$

where
b: Base length of the base mirror

With ELCOMAT 2000 or ELCOMAT vario the measurement is more precisely and the measurement tim decreases rapidly.



Planarity Measurement

Set-up:

- Autocollimator with double micrometer, collimator reticle S115 (cross line) and eyepiece reticle S127 (double cross line)

or

- Autocollimator with collimator reticle S115 (cross line) and eyepiece reticle S411...S445 (reticle with angle graduation)

or

- ELCOMAT

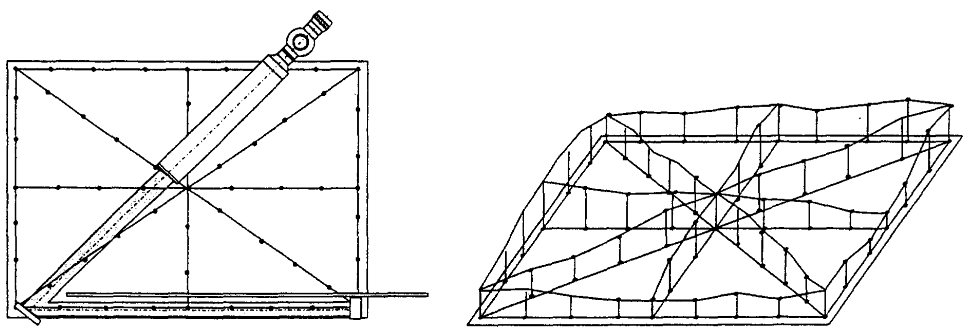
and

- Base mirror
- Deflecting mirror
- Adjustable holder

For the measurement of planarity of surfaces several straightness measurements (p. 3-5) are carried out. The straightness measurements form a geometrical pattern, e.g. the "Union Jack" pattern (fig. a). The deflecting mirror is put at one end of the line of measurement and adjusted such, that the light beam from the autocollimator is deflected in the direction of measurement. A straightness measurement is carried out using the base mirror. A ruler can be used as a guide way for the base mirror. This procedure is repeated for the other lines of measurement.

The height profile of the lines is combined to a two dimensional pattern, here the "Union Jack", by linking at the intersection points (fig. b). This evaluation is most easily carried out on a computer, for which a special evaluation software is available.

With the use of the ELCOMAT 2000 or ELCOMAT vario the accuracy can be increased with an even shorter measurement time. In this case the time-consuming manual data input is dropped.



a) b)

Squareness Measurement between a Vertical Spindle and a Machine Bed

Set-up:

- Autocollimator with double micrometer , collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (single crossline) and eyepiece reticle S441...S431 (reticle with angle graduation)

and

- Adjustable holder
- Tripod
- Two plane parallel mirrors
- Pentagon prism with wedge

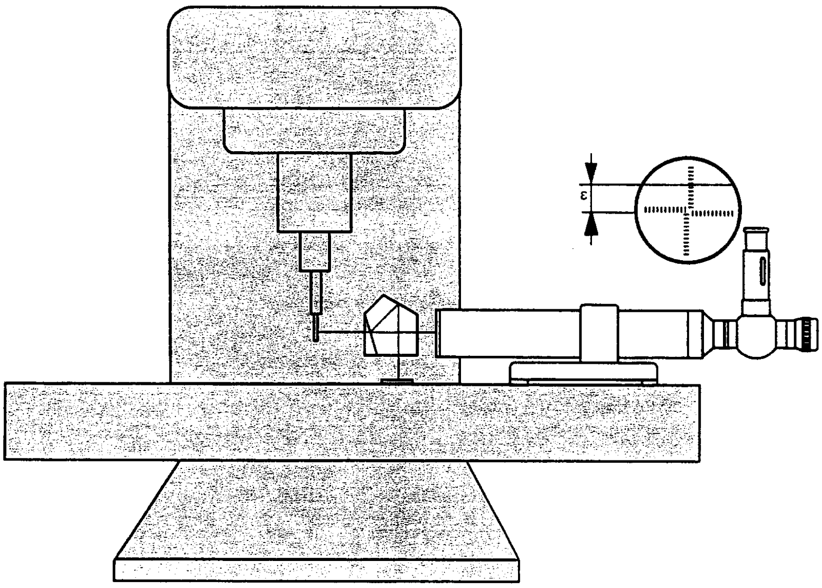
The measurement is done in two steps:

1. The Autocollimator is adjusted in straight view through the pentaprism to the plane parallel mirror at the spindle. Then the mirror is turned by 180° around the spindle axis. The vertical deviation of the reticle image is read out and divided by two. The mirror is realigned by this value. After a second rotation by 180° the vertical deviation should remain constant.
2. A second plane parallel mirror is put on the machine bed. By the pentagon prism the light bundle is deflected onto the second mirror, so that a second autocollimation image appears. The deviation from squareness can be calculated directly from the vertical distance of the autocollimation images according to:

$$\Delta\varepsilon = \frac{\Delta y}{2f} \qquad \text{or} \qquad \Delta\varepsilon = \Delta\varphi$$

where:

Δy, $\Delta\varphi$: Vertical distance of the autocollimation images,
f: Focal length of the autocollimator



Parallelism Measurement of Cylindrical Bore Holes

Set-up:

- Autocollimator with double micrometer, collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle with collimator reticle S115 (single crossline) and eyepiece reticle S304 (reticle with mm-graduation)

or

- ELCOMAT

and

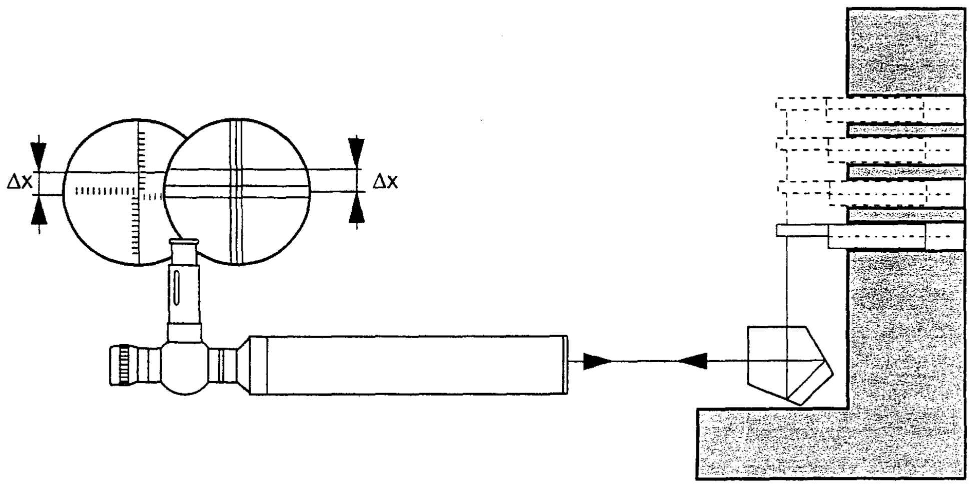
- Pentagon prism
- Flat mirror
- Adjustable holder

The mirror is fixed to the head side of a spine. The spine is placed in the first hole and the autocollimator is adjusted until the image is reflected in the middle of the measuring range. If test holes in parallel above each other a pentagon prism is used to deflect the light bundle by 90°. Read out the position of the micrometer drums or the eyepiece reticle with mm graduation. Then the spine is placed into the next hole. Again the values must be registered, and this must be done for each hole. Read the valued Δy or $\Delta\varphi$ and calculate the angle α between axes of bore holes as per :

$$\boxed{\alpha = \frac{\Delta y}{2f}} \quad \text{or} \quad \boxed{\alpha = \Delta\varphi}$$

where

Δy, $\Delta\varphi$:	Distance of the autocollimation image from Zero (coincidence) position
f	Focal length of the autocollimator.



Testing of Accuracy of Rotary Tables and Index Tables

Set-up:

- Autocollimator with double micrometer, collimator reticle S115 (cross hair) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S 411 ... S431 (reticle with angle graduation)

or

- ELCOMAT

and

- Polygon
- Adjustable holder

Adjust the reading of the rotary table position indicator or of the index table in such a manner, that a whole number is displayed. Place a polygon on the table and adjust the autocollimator to one of the surfaces in such a manner that the image of the projected reticle is in the centre of the eyepiece reticle.

There are two measuring methods:

1. Rotate the table with polygon by angle 360°/n (n – number of polygon sides). Measure the distance Δx relative to the zero position with the aid of the double micrometer. The error is determinated as per:

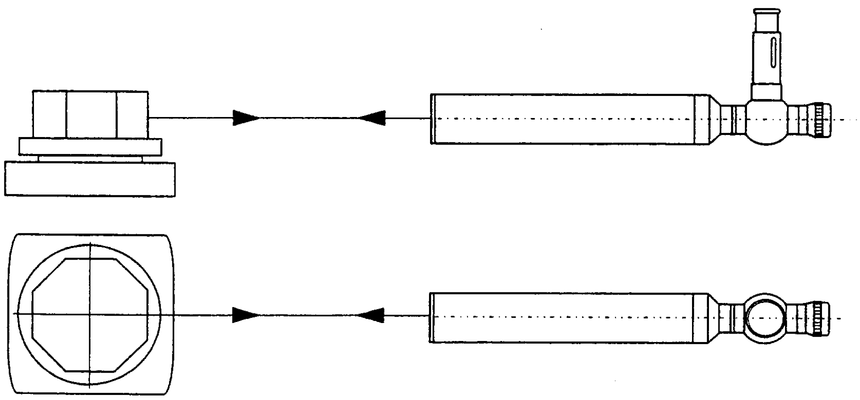
$$\Delta\varphi = \frac{\Delta x}{2f}$$

where:
Δφ: error of the table in measured area
Δx: distance of the autocollimation image from its zero-position
f: focal length of the autocollimator

2. Rotate the table with polygon until the autocollimation image of the next polygon surface is in the centre of the eyepiece reticle. Read out the angle position of the table. The error is determined as per:

$$\Delta\varphi = \frac{360°}{n} - \varphi$$

where
Δφ: error of the table in measured area
n: numbers of polygon surfaces
φ: angle position read out of the table



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（出國報告書）

本授權書所授權之出國報告書名稱：

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