Geometrical Quality Control In Nuclear Power Stations
A Procedure For High Precision Underwater Photogrammetry

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This paper is dedicated to Gotthard Heiskel for his personal engagement in this project. He died in November 1985.

1. General introduction

Nowadays the peaceful use of nuclear energy plays an important role in power industry. The Rheinisch-Westfälisches Elektrizitätswerk AG (RWE), the greatest generator of electrical energy in Europe, produces about 20% of it's output by means of this technique.

An essential part of a nuclear power plant is realized by the fuel assemblies (FA) which contain the nuclear substance. One central topic within the scope of FA-technique is the periodical supervision of their physical status. In the last few years the observation of oxidation processes and length changes of FA's as well as visual inspection have contributed to improve the layout and manufacturing of FA's. Recently, deformations of FA's like relative shift and torsion are examined with great interest (*Baur et al. 1988*). These deformations cause temporal delay when charging the core during a revision, and as a result they reduce economy essentionally.

Special advantages of photogrammetric techniques like non-contact measuring, short duration while taking the exposures, photographic object documenation etc. are important arguments to use photogrammetry in nuclear plants.

2. The object

The design of the FA's depends on the power size and type of

the reactor. The FA's used in this case are square bundles with 16*16 positions. 20 of these 256 positions are occupied by the control rod guide tubes which, together with the 9 spacer grids and the head- and foot-pieces, constitute the structure (the skeleton) of the FA (Fig. 1 and 5). The total height of the FA is about 4700 mm, length and width are 230 mm each. It consists of special alloy metals, fitted to the needed necessaries like stability, thermal behavior etc.
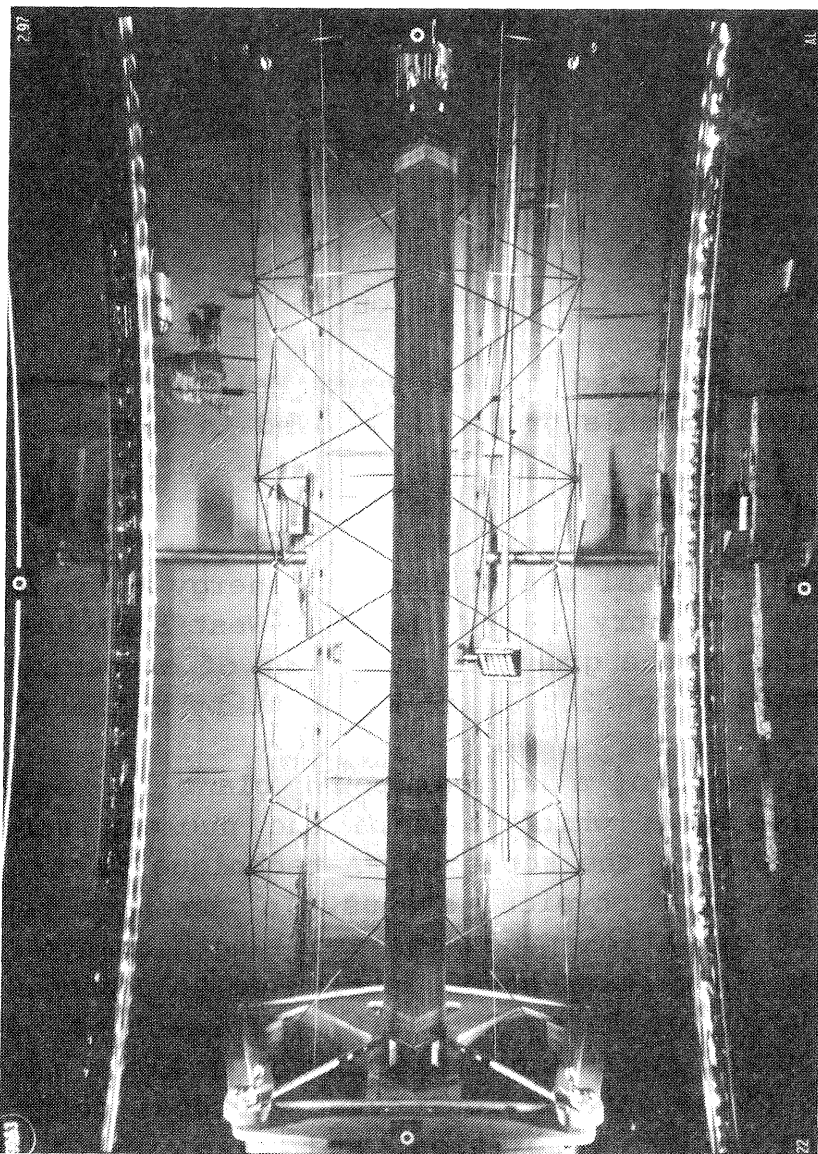

Fig. 1   Example of underwater image. FA and framework are fixed to the baseplate. Left and right flashlight tubes are visible, which, in case of refraction, are apparently bended.

Used FA's are sources of high nuclear radiation and have to be handled in protected underwater areas, complicating any surveying procedure.

Nevertheless, photogrammetry contents a lot of features which give the method enough efficiency for use in nuclear plants.

3. Design of the surveying layout

In November 1986 first experiences were made with underwater photogrammetry in Biblis plant. 6 FA's were surveyed in order to derive the efficiency of underwater photogrammetry but also to get deeper experiences in positioning the refuelling machine when charging the core.

The photogrammetric aspects will be discussed more detailed. To prepare a high precision measurement of FA's by means of underwater photogrammetry lots of preparations have to be done before starting the campaign; this concerns hard- and software developments as well.

First the whole photogrammetric equipment had to be adapted to the special requirements in the nuclear power plant. A certain location had to be chosen to do the measurements, in this case the FA storage spool. The measuring arrangement is shown in fig. 2 - 3.
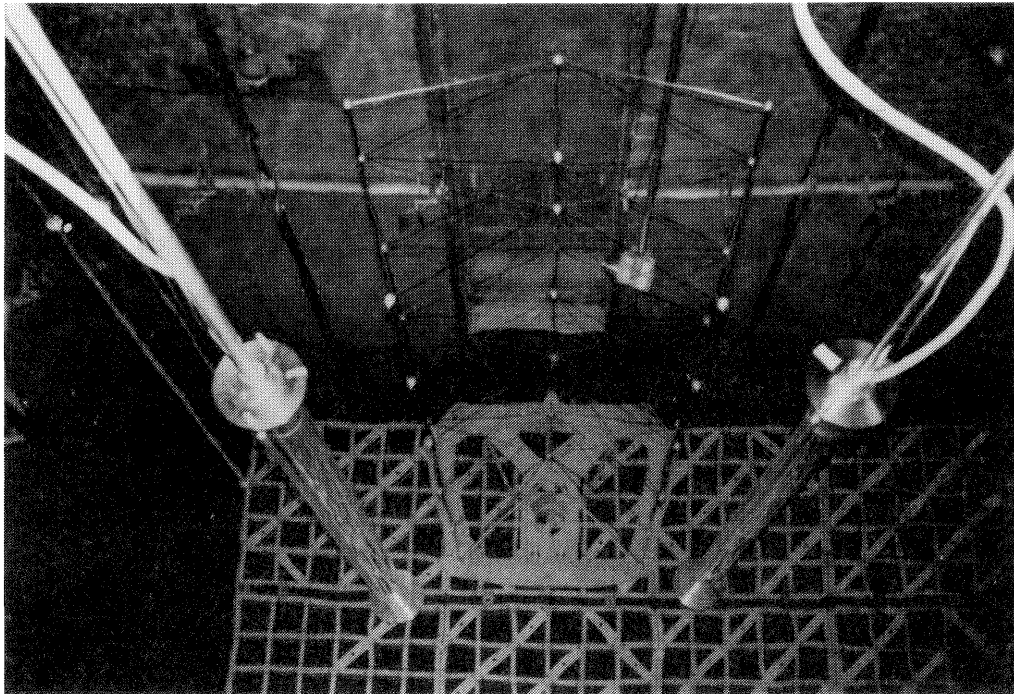

Fig. 2 View into the FA storage spool

The FA to be measured is placed on a horizontal baseplate which itself is positioned on the compact storage frame. The setting-up of the FA is done in a way, that two of it's sides are visible when taking photographs. A rigid framework surrounds the FA. In the junctions of the framework signals have been fixed. These signals are used as control points for the following calculations.
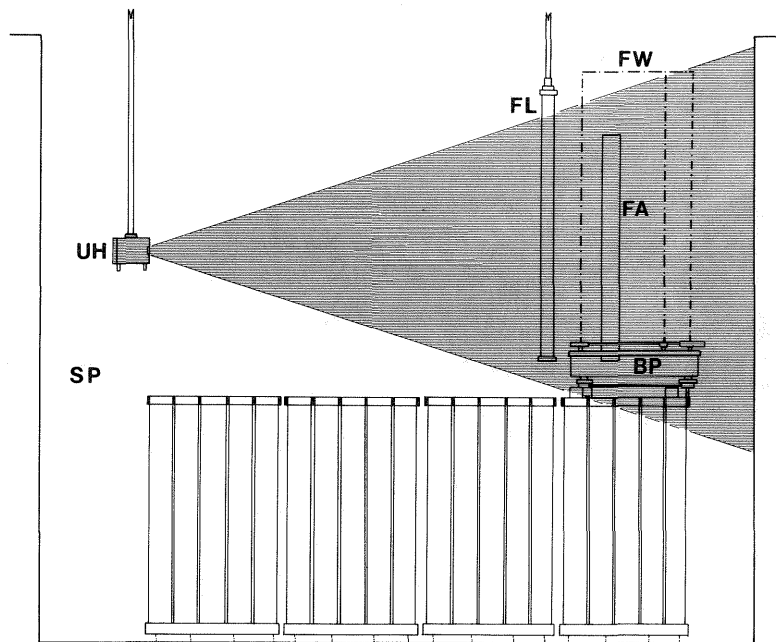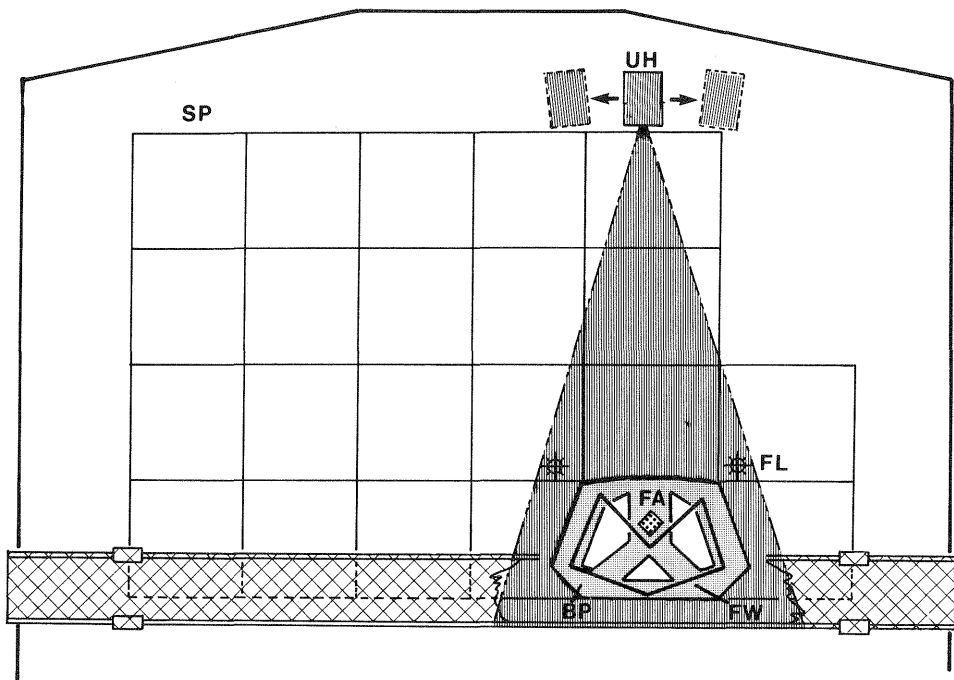
Fig. 3a and 3b Measuring arrangement (ground and side view)

SP - storage spool   UH - underwater housing with UMK
FL - flashlight-tubes   FW - framework
FA - fuel assembly   BP - baseplate

The framework had been calibrated photogrammetrically at the beginning and the end of the campaign. Using photogrammetric deformation analysis, in context with bundle block adjustment,the very high stability of the framework could be proven (*Hartfiel 1987, Hinsken et al. 1987*).

Left and right from the baseplate flash-light tubes are positioned to guarantee a homogeneous lighting of the FA and the framework. Fixed in an underwater housing (Fig. 4) a universal measuring camera, UMK 10/1318, by Zeiss Jena is used. A plane-parallel window (thickness 25 mm), placed some millimeters in front of the camera objective, allows an unchecked look to the object. The underwater housing itself is tight to the refuelling machine. While the FA and the framework are fixed on the baseplate, the underwater housing can be positioned by movements of the refuelling machine as necessary. Camera and flash-light tubes are radio-controlled.
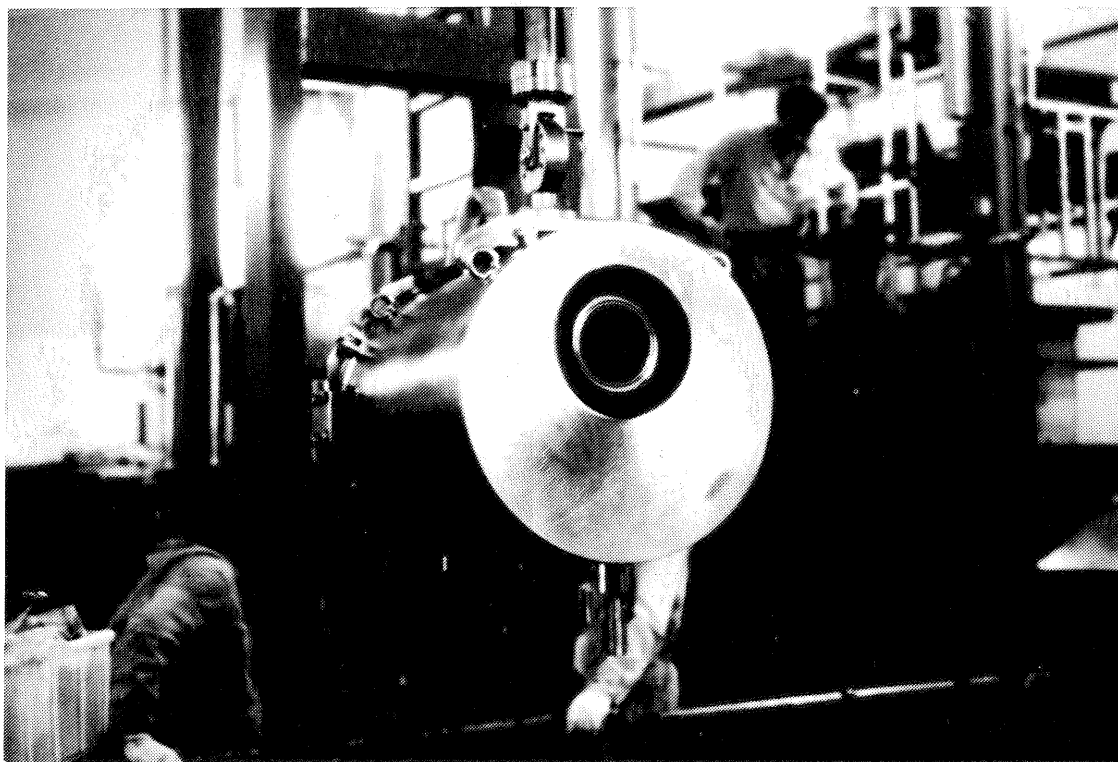

Fig. 4 Underwater housing

Although the UMK is designed for use in air, this camera, fixed in an underwater housing, was prefered because of the large image format (13 cm * 18 cm), leading to acceptable surveying periods. This is a very important aspect, particularly when measuring a greater quantity of FA's.

Two other very important parts of the surveying system, beneath the already mentioned ones, are build by the film-filter combination. Some tests had be done preparatory to find a optimal combi-

nation of these materials.

4. Evaluation concept

Purpose of the project is the determination of parameters describing unambiguously the shape of the fuel assemblies, represented by its spacer side plates. One essential intermediate step to fulfill this task is to calculate the spatial position of the surface elements F_i (Fig. 5) which should be planes if perfectly produced.
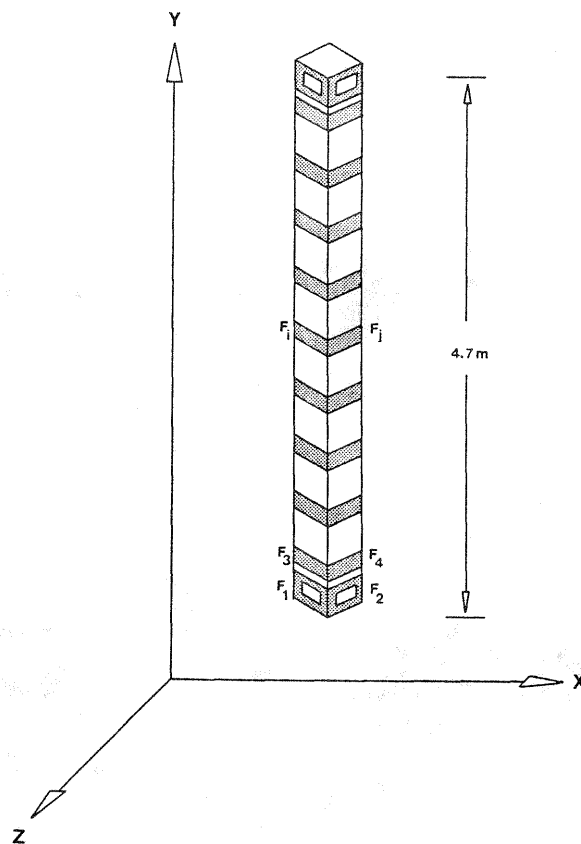

Fig. 5   Skeleton of the FA showing spacer side plates, head- and foot-piece

The definition of all surface elements can be derived by measuring photogrammetrically a sufficient number of surface points. The determination of surface points can hardly succeed by measuring in the comparator mode, because a successive identification of homologous image points is nearly impossible. Therefore, it was necessary to perform the measurement of surface points in oriented stereo models. The following rough classification gives an overview about the most important steps which have to be run through:
- determination of orientation parameters by extended phototrian-

gulation;

- set up of stereo models considering simultaneously refraction effects;

- stereo measurement of surface points and derivation of parameters describing the FA.

4.1 Phototriangulation with light refracting surfaces

The FA was embedded in a framework of 17 regular distributed control points (Fig. 1) which coordinates are known in a local coordinate system with an accuracy of $\pm$ 0.06 mm in X- and $\pm$ 0.09 mm in Y- and Z-direction (calculated by photogrammetric bundle block adjustment). The control points are imaged in all photos and these image points were measured on a Planicomp C100 in order to determine the orientation of the image block.

Concerning image quality it is to be mentioned that the lens system of the UMK is designed to reduce image aberrations to a minimum when used in air. The application of this camera underwater in a pressure-proven and watertight housing leads to distorted and non-stigmatic imaging caused by light refraction at the boundary surfaces between different media (water, glass, air). Thus, the control points of circular shape are extremely deformed to image patches of elliptic shape (Fig. 6) complicating the definition of homologous image points.
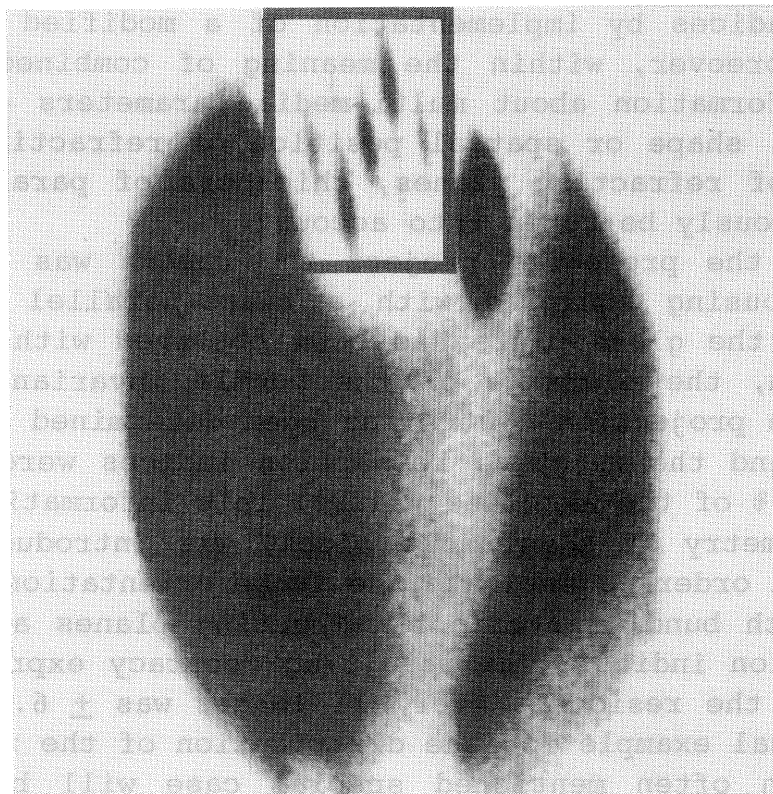

Fig. 6   Image of extremely deformed control point signals (see
          frame)

The attempt to coincide the floating mark and the centre of gravity of the grey level patches succeeded with an accuracy of $\pm$ 4.3 µm in x- and $\pm$ 8.0 µm in y-direction derived from multiple measurement. The significant lower accuracy in y-direction is a result of stronger distortion caused by greater inclination between refraction planes and image rays. An improvement of the image quality can be achieved with special underwater lenses or with correcting lens systems (*Ivanoff 1951, Wakimoto 1967, Adams 1982, Baldwin 1984, Fraser et al. 1986*; see chapter 3).

The orientation parameters were determined by bundle triangulation. The conventional functional model for bundle triangulation is based on central projection and deviations of collinearity between object point, projection centre and corresponding image point (e.g. lens distortion, atmospheric refraction) are normally corrected by specific image functions. But the efficiency of such a procedure is only limited to compensate the refraction of light rays caused by refracting surfaces in object space. The application of an extended functional model for phototriangulation in multi-media photogrammetry becomes desirable as suggested by Newton (*Newton 1984*). On the basis of the bundle adjustment program MOR-S (*Hinsken 1985, Wester-Ebbinghaus 1985*) such an extended functional model has been realized (*Kotowski 1988*). Besides the estimation of image orientation parameters and the coordinates of object points the program allows to estimate simultaneously parameters of light refracting surfaces and relative refraction indices by implementation of a modified ray tracing algorithm. Moreover, within the meaning of combined adjustment available information about multi-media parameters or functions of them (e.g. shape or spatial position of refracting surfaces, parallelism of refracting planes, thickness of parallel planes) may simultaneously be taken into account.

Concerning the presented project the camera was fixed in an underwater housing equipped with a plane-parallel window. The thickness of the glass plate had been observed with an accuracy of $\pm$ 0.03 mm, the distance of the bundle invariant refracting planes to the projection centre had been determined within a few centimeters and the relative refraction indices were known in a range of $\pm$ 1 % of the absolute values. This information, stabilizing the geometry of the bundle block, was introduced into the adjustment in order to estimate the image orientations, the parameters of both bundle invariant refracting planes and the relative refraction indices. The resulting accuracy expressed by the rms value of the residuals over all images was $\pm$ 6.8 µm. Fig. 7 shows a typical example for the distribution of the residuals.

Finally, an often mentioned special case will be considered briefly. If the optical axis intersects the refracting planes perpendicular, it is possible to compensate the refraction ef-

fects by introducing functions for radial distortion which are dependent on the exposure distance (e.g. *Rinner 1969*, *Höhle 1971*, *Dorrer 1986*, *Kotowski 1987*). The assumption of such a condition within this project led to a significantly increased rms value of ± 10.3 µm for all image residuals and systematic effects become visible (Fig. 8).

The attempt to express all appearing image deformations with radial and decentering distortion also led to a rms value of ± 10.3 µm for all image residuals.

The functional model for the imaging process is not properly chosen, if inclination parameters between refracting surfaces and optical axis are omitted.
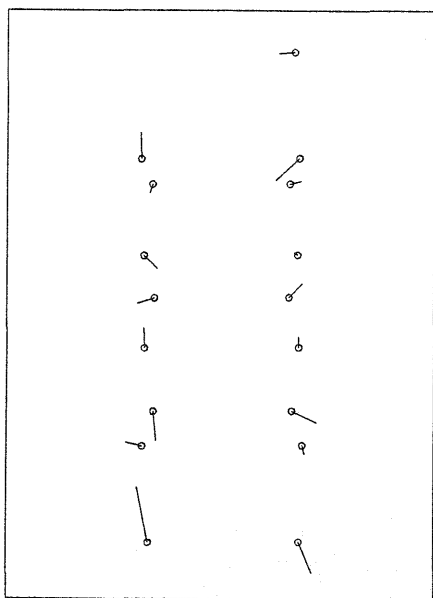
IMAGE 1013
⊢—⊣ = 10 MM IN THE IMAGE
⊢—⊣ = 10 µM VECTOR LENGTH
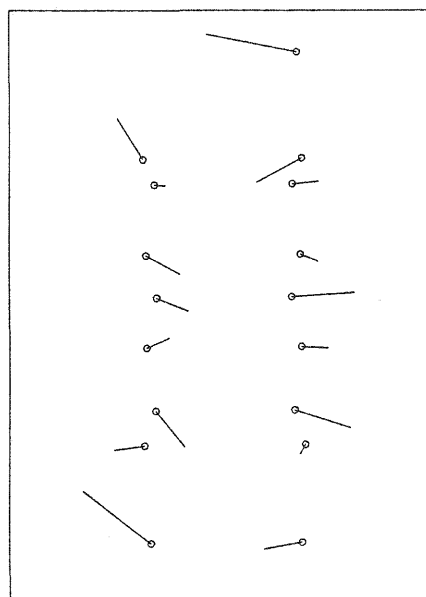
IMAGE 1013
⊢—⊣ = 10 MM IN THE IMAGE
⊢—⊣ = 10 µM VECTOR LENGTH

Fig. 7 Phototriangulation residuals; refracting surfaces are estimated.

Fig. 8 Phototriangulation residuals; refracting surfaces are parallel to the image plane.

4.2. Stereo models in multi media photogrammetry

The interior and exterior orientation parameters calculated by phototriangulation were transferred to the analytical plotter to set up stereo models. But in case of multi media restitution the refraction indices and the surface parameters belong to the ori-

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entation data. Strictly speaking it is necessary to extend the conventional central perspective loop of the analytical plotter for tracing the refracted rays (*Kotowski 1987*). Such a procedure has been realized by Masry and Konecny for two media restitutions considering a refracted plane (*Masry et al. 1970*).

Instead of integrating a ray tracing procedure into the analytical plotter's loop there is an alternative when dealing with bundle invariant refracting surfaces: the physical description of the light rays may be replaced by describing the refraction effects in the image plane. These refraction effects are for any point expressed by differences between two image positions of the same object point, projected with and without ray tracing through the refracting surfaces (Fig. 9). The figure shows, that the effect is mainly radial symmetric but, as derived in chapter 4.1, purely compensation of radial symmetric distortion is not sufficient for the functional model.
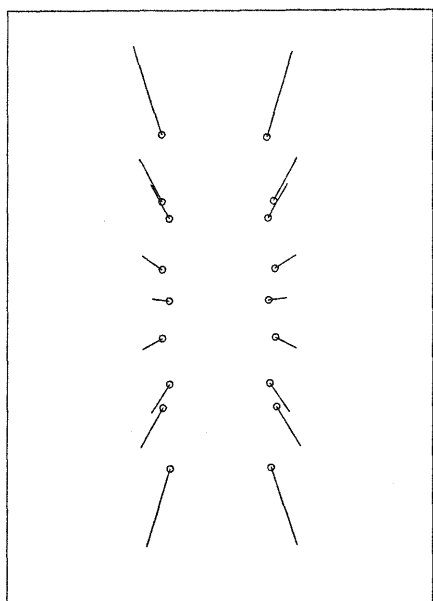
IMAGE 1013
⊢—⊣ = 10 MM IN THE IMAGE
⊢—⊣ = 10 MM VECTOR LENGTH

Fig. 9   Difference between
         points projected with
         and without refracting
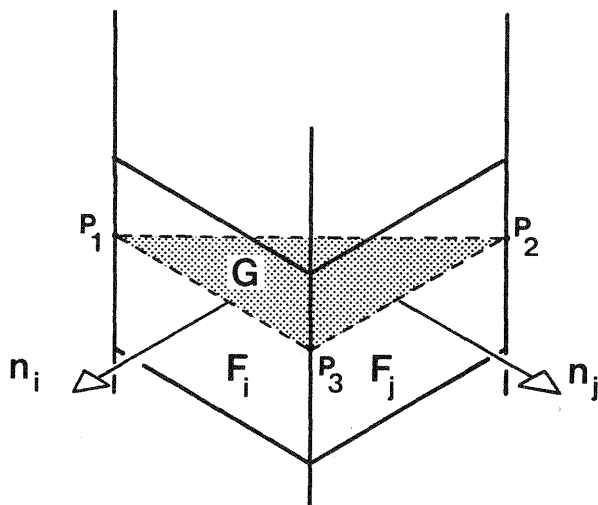   surfaces.

Fig. 10   Definiton of FA
          shape parameters
          by calculated
          triangles.

The computed difference vectors are the basic information to calculate a correction grid for on-line shifting of the plotter's floating mark from the central perspective position to the real image point. The final result is a sufficient parallax-free ste-

reo model. Such a procedure was adopted for the multi media stereo pairs in this project by applying on-line correction for compensating systematic image errors (*Kotowski 1984*).

Further applications concerning stereo restitution of multi media image pairs are published by *Kreiling 1970; Pollio 1971; Rosencrantz 1971; Jacobi 1980; Masry et al. 1980; Welsh et al. 1980; Fryer 1982; Elfick et al. 1984; Welham 1984.*

4.3. Derivation of shape parameters

With the help of the surface elements F_i the shape of the spacer side plates may be described. Therefore, in a first step, the spatial positions of these surface elements (see fig. 5) were defined by measuring a sufficient dense grid of surface points in oriented stereo models. They could be determined with an accuracy of $\pm$ 0.4 mm in X- and Y- and $\pm$ 1.1 mm in Z-direction. Depending on the intersection geometry a proportional accuracy of 1:4300 up to 1:11750 of the principle object field dimension could be achieved justifying the term high precision point determination for underwater applications (cf. *Fraser et al. 1986*). The surface points were used to estimate the plane parameters. The quality of this estimation can be described by the deviations between the surface points and the corresponding adjusted planes. A rms value of $\pm$ 0.5 mm could be achieved. Within the limit of the point determination accuracy this result confirms the assumption of planes.

On eleven levels of the elongated object there are always two planes, lying opposite to each other. For each of these two-plane-elements the corresponding normal plane G intersects the planes F_i and F_j in a chosen average height and defines the triangle P_1, P_2 and P_3 (see fig. 10). Such a triangle has been calculated for each group. Their inclination, position and rotation describe displacement and torsion of the entire object. Fig. 11 shows a perspective view of these triangles.

So a few essential shape parameters of a rather complex object could be derived from a photogrammetric point determination; they form a well defined basic information to compare several epochs and are therefore suitable for periodical inspections.

5. Conclusions and future aspects

The measurement of nuclear radiation emitting FA's by means of high precision underwater photogrammetry could be shown. Specially built constructions for taking underwater images and a flexible procedure of analytical and numerical multi media photo-

grammetry for the evaluation of form parameters could be realized.

The UMK fixed in an underwater housing proved true, although the employment of an underwater camera or special correcting lens systems surely would improve the image quality. Some further experiences also have to be done to find the optimal film-filter combination.

Orientation data for a stereo restitution were derivable by photogrammetric phototriangulation with consideration of light refracting surfaces . These orientation data were used to set up stereo models in an analytical plotter. The refraction effects were compensated by means of on-line correction. The stereo restitution is limited to applications with bundle invariant refracting surfaces. For stereo restitutions of image pairs distorted by object invariant refracting surfaces the integration of a ray tracing algorithm into the projection loop of the analytical plotter is recommended.
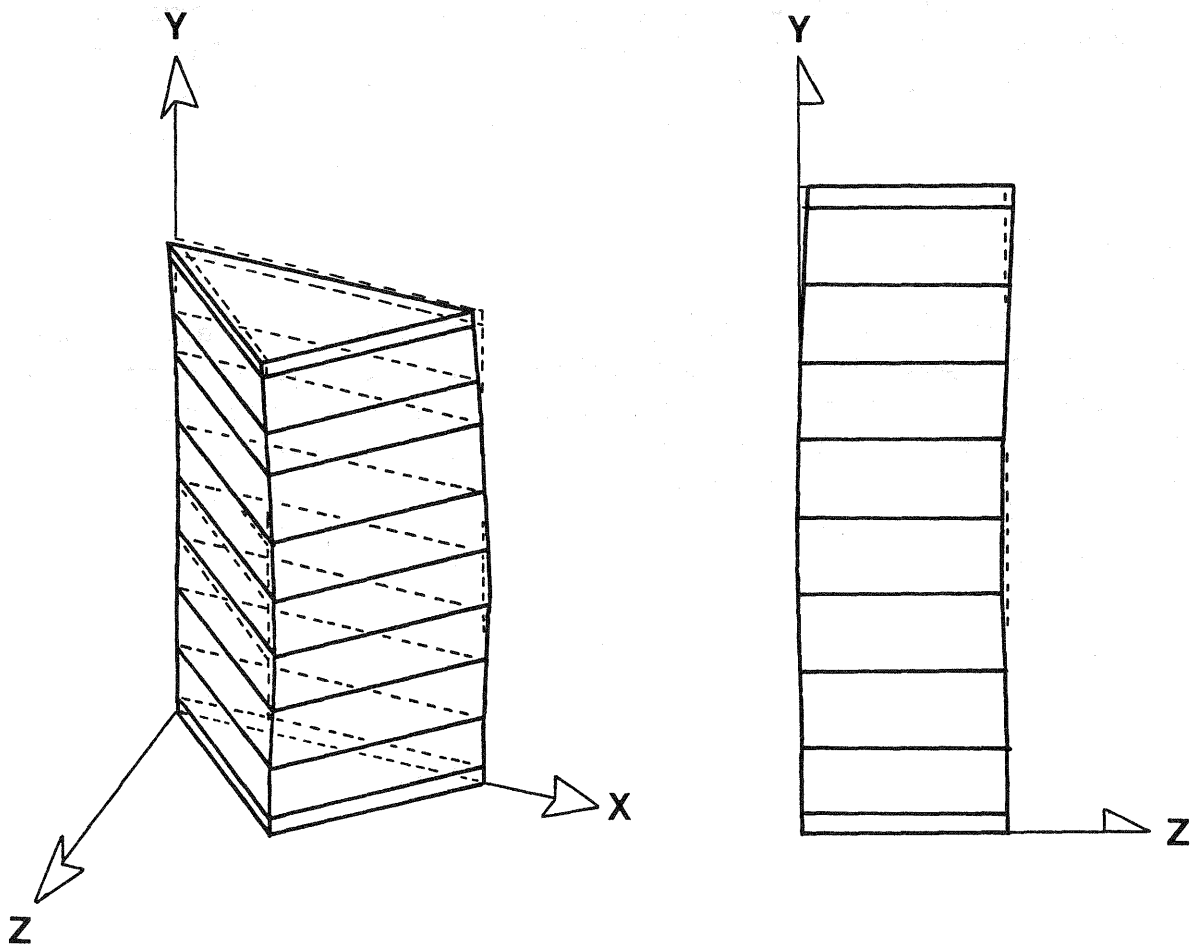

Fig. 11 Perspective view of a measured FA

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BuL   - Bildmessung und Luftbildwesen
DGK   - Deutsche Geodätische Kommission
IAP   - International Archives of Photogrammetry
PE   - Photogrammetric Engineering
PR   - Photogrammetric Record
PWS   - Proceedings of the photogrammetric week at Stuttgart University
ZfV   - Zeitschrift für Vermessungswesen

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