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BEST-FIT ADJUSTMENTS OF THE REFLECTORS IN A COMPACT RANGE[1]

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ABSTRACT

ESA's Compact Antenna Test Range at ESTEC has been relocated which has given the chance to improve the alignment of the reflectors. Based on measurements of the reflector surfaces the best-fit positions and orientations of the reflectors have been determined. It turned out that the choice of parameters to describe the reflectors and their position had important impact on the optimization process: The parameters shall – as far as possible – be orthogonal in the sense that a change in one parameter must not influence the final value of the other parameters.

Keywords: Compact range modelling, surface fitting, reflector adjustments, optimization.

1. Introduction

The Compact Antenna Test Range (CATR) at ESTEC, Figure 1, has been relocated to a new chamber close to the other test facilities at ESTEC. The range is designed as a double reflector range by March Microwave Systems [1] and was built in order to get experience of compact ranges before the large Compact Payload Test Range (the CPTR) at ESTEC was built. The CATR is designed for the frequency range 4-18 GHz.

Due to the manageable size of the two reflectors it has been possible to move them without dismantling the reflectors from their back structure.

After the relocation it was necessary to ensure that the surfaces of the two reflectors were not deteriorated by the removal. Therefore, the surfaces of the reflectors and some critical mounting points were – before and after the relocation – measured by a laser tracking system. Based on the latter measurements, it was desirable to determine the optimum position and orientation of the reflectors as well as to find the performance of the range up to 30 GHz.

The paper first gives a short description of the geometry of the range in Section 2 and a presentation of the range before the relocation in Section 3. The optimization method and the chosen optimization variables are described in Section 4 and the deviations of the measured surfaces from the best-fit surfaces are presented in Section 5. The parameters for the best-fit surfaces are given in Section 6 and the conclusions are drawn in Section 7.

2. The geometry of the CATR

The reflectors of the CATR are designed as two singly-curved parabolic surfaces [1]. The beam from the feed (F, Figure 2) illuminates the subreflector which is curved vertically and therefore collimates the beam to a horizontal beam directed towards the main reflector. The main reflector is curved horizontally and will therefore collimate the beam in the horizontal plane towards the quiet zone. The solid part of the main reflector is 1.7m × 3.2m.

The reflectors are equipped with serrations along the edges. These follow the same singly curved surface as the solid part of the respective reflector, cf. Figure 1.

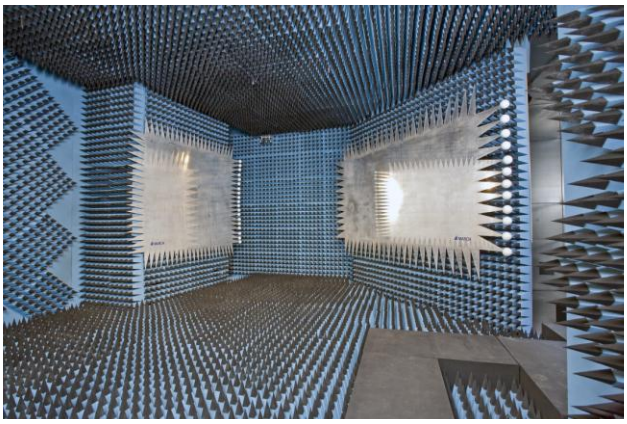

Figure 1 – The CATR after relocation, main reflector to the right, subreflector to the left. The feed is hidden in a niche to the right behind foreground absorbers.

The reflector surfaces are designed on the basis of Geometrical Optics (GO). As the reflectors are singly curved they do not possess focal points but focal lines each of which corresponds to the focal point of the parabola which is the two-dimensional directrix for the surface. In order to have the double reflector system working correctly, the focal line of the subreflector must be horizontal through the range feed *F* and parallel to the generatrix of the subreflector, Figure 2(a). Rays in a vertical plane from the feed will all be reflected horizontally in the subreflector which is a 'vertical' parabola. Rays from the feed in a plane perpendicular to the vertical plane will also reflect horizontally in the subreflector, Figure 2(b), but the rays still diverge as the subreflector is a straight line in a horizontal cut. These horizontal rays from the subreflector will all have directions from points on a vertical line behind the subreflector. This line shall coincide with the focal line (vertically through F_l, Figure 4) for the main reflector.

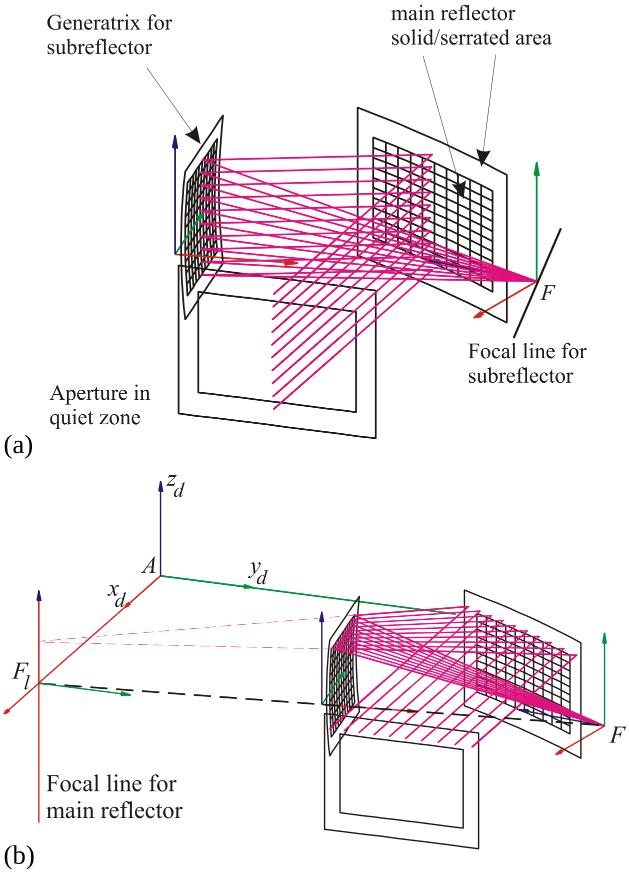

Figure 2 – Illustration of the singly curved double reflector range. The GO rays are collimated vertically by the subreflector (a) and horizontally by the main reflector (b).

Another vertical line, through *A* (Figure 4) constitutes the apex of the main reflector parabola. *A* is chosen as origin for the design coordinates (x_d,y_d) and the aperture plane will be parallel to the $y_d z_d$-plane.

3. The range before relocation

Before the range reflectors were moved the surfaces of the reflectors were sampled by a laser tracking system, Figure 3. Also the positions of reference points on the supports of reflectors, feed and quiet-zone positioner were sampled.

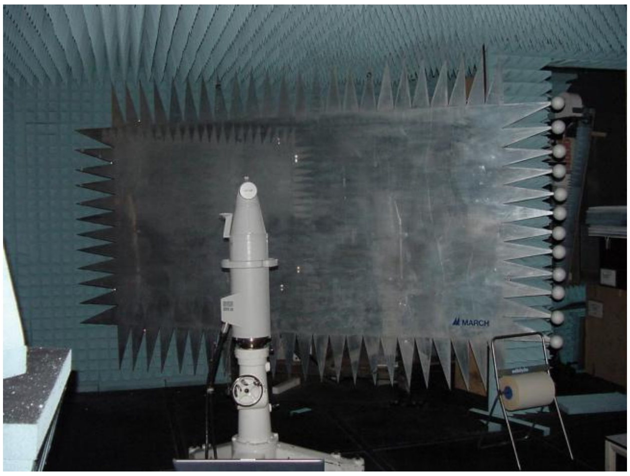

Figure 3 – The laser tracker in front of the main reflector before relocation.

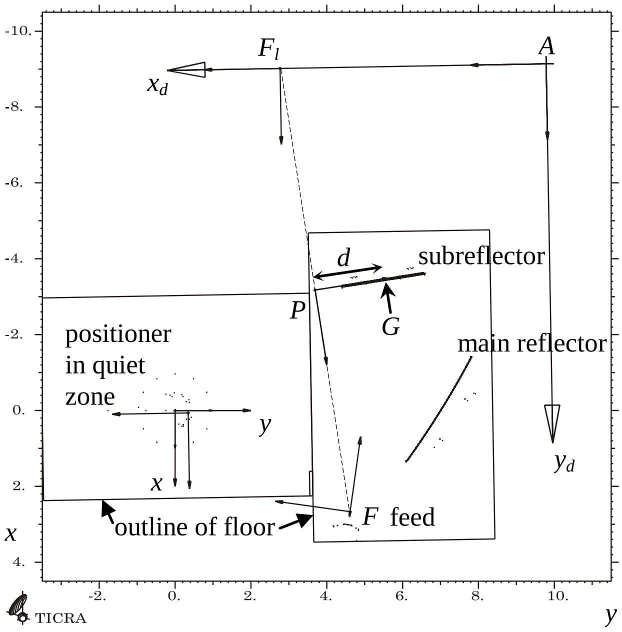

Figure 4 – The geometry of the CATR before relocation given by the points sampled by the laser tracker. The outline of the floor is illustrated by two rectangles.

All sampled points are plotted in Figure 4 in the *xyz*-coordinate system of the laser tracker. The reflectors are identified by the many points sampled over the solid parts of the reflectors.

The geometry of the CATR after relocation has also been measured by the laser tracking system. A plot of the sampled points will have a look as in Figure 4.

4. Determination of best-fit reflector surfaces

The parameters of the best-fit parabolic reflector surfaces are determined from the sampled points by an optimization. A best-fit parabolic cylinder shall be fitted to each sampled surface in such a way that the two reflectors and the feed can be aligned correctly.

The position and orientation of a reflector system may be described by six parameters, or six degrees of freedom. Thus, a simple front-fed paraboloidal reflector system may be described by three parameters for the position of the focal point and two for the direction of the axis. The last, sixth, parameter may be used to define the focal length. When the paraboloid is given, the focal length can not be varied, and the same is the case when a best-fit surface is determined from a set of measured points. Thus, five independent variables are available for the optimization, the sixth shall be determined as a result of the optimization.

The choice of the five independent variables is not simple as the chosen variables preferably shall be unrelated. Ideally, the surfaces of the CATR are two-dimensional parabolic surfaces. In a suitable coordinate system such a surface may be invariant along *z* and described by a parabola (the directrix) in the *xy*-plane. The surface may conveniently be defined by the following five variables: Two variables define the direction of the *z*-axis and two more variables define the position of the focal point in the *xy*-plane. The fifth variable could be the direction of the axis of the parabola. The goal of the optimization is to determine the focal length of the parabola having minimum deviation to the measured set of points.

However, this description is not the best for an optimization procedure because the base described by the first variables must be changed when the following variables are defined. Thus, values for the first five parameters define a set of parabolas in the *xy*-plane with different focal lengths but all with the same focal point, cf. Figure 5. Finding the best-fit parabola requires changing the focal length whereby the parabola moves considerably. Such ties between the parameters turn out to hamper the optimization, and other, better posed optimization variables must be chosen. In the example, the set of parabolas could be described with a common apex. Hereby the shape of the parabola can be changed without moving the parabola itself.

The two reflectors of the CATR have different functions so the chosen optimization variables are therefore different. We shall first consider the main reflector.

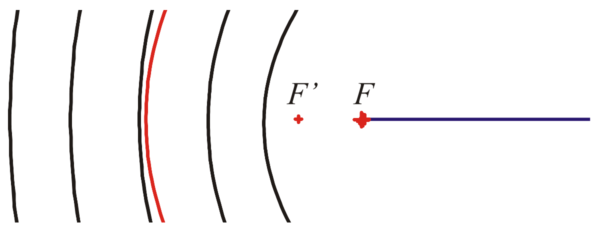

Figure 5 – Parabolas with focal point at *F* and different focal lengths (black). The parabola which fits best to a measured parabola (red) requires the focal point to be moved to *F'*.

4.1 The main reflector

The purpose of the main reflector is to produce a plane wave in an aperture across the quiet zone of the range. The ideal incident wave is a cylindrical wave with the focal line of the main reflector as axis. The five parameters for the optimization are therefore chosen to define the position and direction of the focal line and the orientation of the aperture plane. The goal of the optimization is to determine the focal length from the measured surface points.

We will apply the *xyz*-coordinate system of the laser tracker as reference system. Here, the *z*-axis is vertical and the *xy*-plane is horizontal, cf. Figure 4. The focal line we are looking for is close to vertical. It can thus be defined by two points at two different heights on the line, namely P_1 and P_2 at the bottom and the top of the reflector, respectively, see Figure 6.

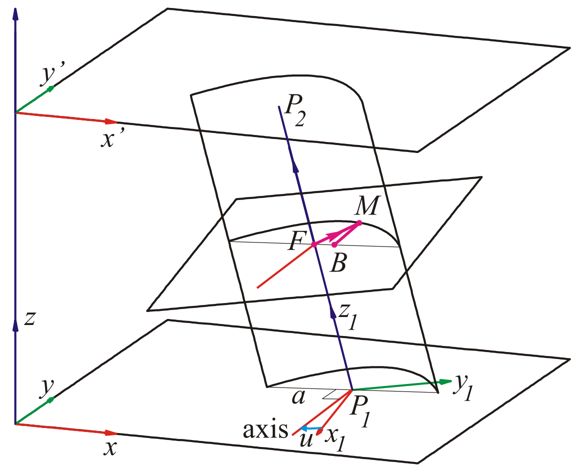

Figure 6 – Determination of the best-fit main reflector. P_1P_2 is the focal line and the aperture plane is spanned by this focal line and the line *a*. The primed coordinates are parallel to the corresponding unprimed.

In the optimization process, the focal line is moved freely as determined by the four independent parameters, (*x*,*y*) and (*x'*,*y'*), defining these two points. Next, a coordinate system, $x_1y_1z_1$, is defined with origin at P_1 and the z_1-axis along P_1P_2, i.e. along the focal line. A parabolic reflector surface with this focal line cuts the x_1y_1-plane in a parabola and the direction of the axis of this parabola can be described by an angle *u* from the x_1-axis. This angle is the fifth free-varying parameter. The aperture plane for the parabolic surface is defined as a plane perpendicular to the axis of the parabola and containing the focal line.

Values are chosen for these five parameters and through each measured surface point, *M*, a parabolic cylinder with the given focal line is determined as follows.

In a plane parallel to the x_1y_1-plane, Figure 6, only one parabola exists through *M* with focal point at *F* where the focal line intersects the plane. A 'ray' is drawn from the focal point *F* via the surface point *M* and perpendicular to the reflector aperture at *B*. The total length of the 'ray' is twice the focal length *f* of the parabola through *M*.

The average value f_{av} of the determined focal lengths for all measured points of the surface defines an average parabolic surface and the rms-value f_{rms} of the focal lengths is determined as a quality measure for this average parabolic surface.

The best-fit surface is therefore found by an optimization in which the five parameters are varied with the goal to minimize f_{rms}. The resulting best-fit surface is given in Section 6.

The above mentioned 'ray' is not assumed to perform an optical reflection in the actual surface, but the 'ray' from the focal line is – after the reflection – assumed perpendicular to the aperture plane. The method is chosen because the field reflected from a parabolic reflector with small surface inaccuracies according to the Huygens principle will build up as a quasi-plane wave in a direction perpendicular to the aperture plane. If a GO reflection had been assumed the rays might not be parallel due to the surface inaccuracies, and cross-over of the rays would occur, but this is not physically correct.

4.2 The subreflector

The subreflector shall transfer a spherical wave from the feed point to a circular cylindrical wave with an axis close to vertical. This axis shall coincide with the focal line of the main reflector when the reflectors are relocated. The subreflector then has a different purpose than the main reflector though they are both parabolic. This is reflected in the parameters for optimizing the subreflector which shall include the position of the feed and the position and orientation of the axis of the cylindrical wave. The goal of the optimization is given by the quality of the cylindrical wave front.

In the optimization the feed point, *F*, may be moved freely with respect to the measured subreflector surface points. The feed position is determined by three parameters, the coordinates of the point.

The axis of the reflected cylindrical wave is defined as follows, cf. Figure 7. The measured surface points of the subreflector have a gravity centre *G*. The centre of the reflector further has an offset *d*, i.e. a distance from the con-focal line FF_l. This offset does not influence the parameters for the best-fit parabolic surface but is related to the position of the feed. It is therefore set to the value of the design case.

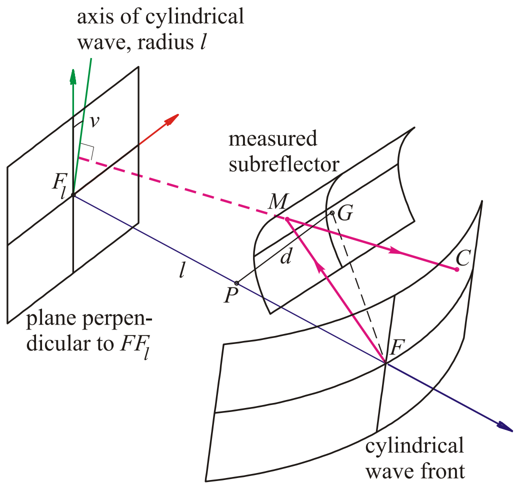

Figure 7 – Determination of the best-fit subreflector. Ray *FMC* equals *l* for the ideal surface.

A point, *P*, is defined at the offset distance *d* from *G* along a generatrix. Initially, the generatrix is set to the direction as given in the design case. A line is then drawn from the feed point *F* through *P*. The distance *l* from the feed along this line defines one point F_l on the axis of the cylindrical wave. The axis is now defined perpendicular to the line FF_l and tilted around FF_l an angle *v* from the normal of the plane FF_lG.

The parameters *l* and *v* are the fourth and fifth parameter to be varied in the optimization. By the parameters it is now possible to determine an ideal circular cylindrical wave front passing through the feed point, i.e. having radius *l*.

The geometry of the actual choice of parameters is evaluated by drawing a 'ray' from the feed point *F* to a measured surface point *M* at which it is 'reflected' in a direction away from the axis of the cylindrical wave, perpendicular to this, and forth to the cylindrical wave front at *C*. The total length of the 'ray' is compared to the radius of the wave front *l* and the rms-value of the differences for all measured surface points is determined. The feed position and the parameters *l* and *v* are varied until a minimum of this rms-value is obtained.

When the feed point is changed, a new point *P* is determined from a new direction of the generatrix which shall be perpendicular to the latest found direction of the focal line.

5. The actual surfaces

When the best-fit parabolic surfaces are found, the measured grid surfaces may be compared to these.

5.1 The main reflector

A coordinate system is now defined with the *z*-axis pointing down range and the *xy*-plane parallel to the aperture, *x* pointing vertically down. Through the measured points a local fifth order spline surface is used to represent the reflector surface as *z*(*x*,*y*) and the difference between this surface and the best-fit parabolic surface is shown in Figure 8.

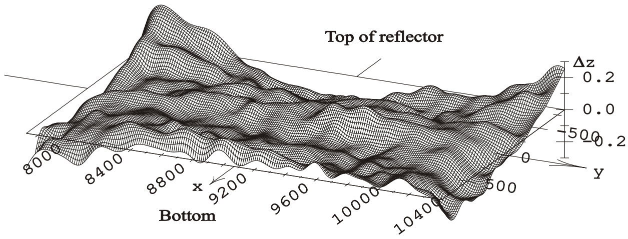

Figure 8 – Main reflector. Deviation (Δz, positive towards the quiet zone) of the interpolated measured surface from the best-fit parabolic surface. All measures are in mm.

The surface of deviations is rather flat. The upper corners of the reflector are bending forward and the lower corners are consequently bending to the back. This is probably due to a gravity deformation as the reflector is hanging on two hooks some distance from the upper corners.

5.2 The subreflector

The deviation of the subreflector from its best-fit surface is shown in Figure 9. The surface coordinate system is chosen with the z-axis parallel to the line F_lF (Figure 4) and positive towards the feed.

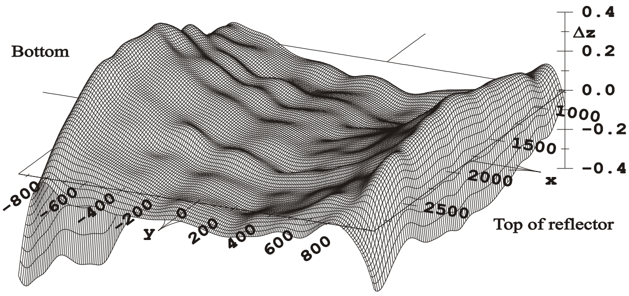

Figure 9 – Subreflector. Deviation (Δz, positive towards the feed) of the interpolated measured surface from the best-fit parabolic surface. All measures are in mm.

Again, a local fifth order spline surface through the measured points is used to represent the reflector surface as $z(x,y)$ and the difference, Δz, between this surface and the best-fit surface is depicted in Figure 9; x is pointing vertically up.

The subreflector is found to have an overall deformation which curves it more than the best-fit parabolic surface over its central part but has a backward tilting of the upper and the lower rims of the reflector. The average value of Δz is, by definition, zero.

Neglecting the outmost parts of the reflector will cause a best-fit parabolic surface resulting in a better model of the central part of the reflector – but the upper and lower parts have a correspondingly larger surface error. The surface deviation of this model is shown in Figure 10 and it is found that this model will give a higher quality of the field in the central part of the quiet zone. This is acceptable as the outer regions of the quiet zone are seldom applied for measurements but more serve as regions in which the edge effects of the reflectors are dying out. The average value of Δz is zero over the part of the reflector (68%) used in the optimization.

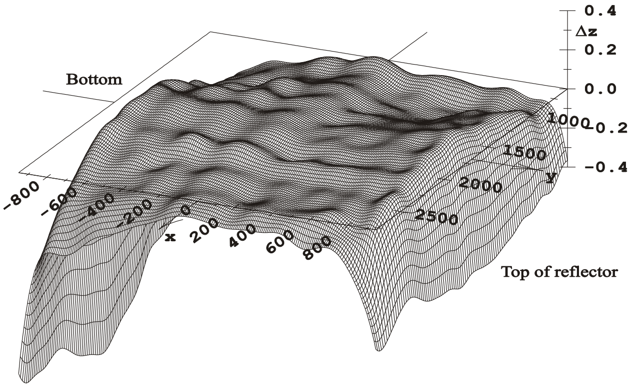

Figure 10 – Subreflector. Deviation (Δz, positive towards the feed) of the interpolated measured surface from the best-fit parabolic surface. All measures are in mm.

A similar exercise has been carried out for the main reflector but the effect is hardly seen in a figure showing the surface deviations.

In Section 4.2, we have not specified a relation for the focal length of the subreflector, but only requested a circular cylindrical wave to be generated. This turned out to produce a best-fit subreflector which cuts the plane FF_lG in a slightly backward curving hyperbola, not in a straight line such as the generatrix. Hereby, the determined surface reflects better in the desired cylindrical wave front.

6 The determined best-fit reflectors

The parameters for the CATR reflectors are given in Table I, both for the original design and for the range before the relocation. The parameters for the moved reflectors were not available at the time of printing, however, Figure 11 shows surface sampling of the subreflector after realignment in the new chamber.

Best-fit CATR parameters			
Parameter (cf. Figure 4)	Nominal design	Before relocation	Difference
Subreflector focal length, half the distance FF_l	5.9152m	5.9112m	-0.0040m
Main reflector focal length AF_l	7.0204m	6.8853m	-0.1351m
Offset, main reflector (distance	9.0380m	9.0740m	0.0360m

from the centre of the reflector to the axis AF_l of the parabolic surface)			
Offset, subreflector (distance from the centre of the reflector to the focal line FF_l)	1.8124m	1.6830m	–0.1294m
'Ray' length rms, main reflector	–	60µm	–
'Ray' length rms, subreflector	–	48µm	–
Surface rms, main reflector	–	43µm	–
Surface rms, subreflector	–	45µm	–

Table I – Important parameters for the CATR reflectors when the outer regions of the reflectors are neglected.

As outcome of the optimization also the mutual position of the reflectors are obtained as well as the position of the feed and an aperture plane in the quiet zone.

7. Conclusions

The surfaces of the CATR reflectors have been measured and the best-fit parabolic surfaces for the reflectors have been found by optimizing the performance of the plane wave in the quiet zone. It has been demonstrated that it is possible to define the shape, position and orientation of a parabolic reflector by six variables, but it has importance for the optimization that the variables are posed with care. This led to a rather sophisticated, but efficient set of optimization variables.

For the main reflector, the deviation of the measured surface from the best-fit surface constitutes a rather flat function with an rms value of 43µm (over the applied central region of the reflector). The upper corners of the reflector bend slightly forwards and the lower corners bend correspondingly backwards, probably due to the way in which the reflector is mounted.

For the subreflector the same deviation has an rms value of 45µm based on the measurements of the central part of the reflector. This value is 30% less than a value based on surface data for the full subreflector for which the top and bottom area bend up to 1 mm backwards.

In the horizontal cut, the subreflector bends slightly backwards. The applied optimization technique utilised this to determine a best-fit subreflector surface not being precisely parabolic but having a hyperbolic cross section with the horizontal symmetry plane of the range. This led to a better positioning of the subreflector surface.

The relative positions of the reflectors have also been determined and measures for alignment of the reflectors are given.

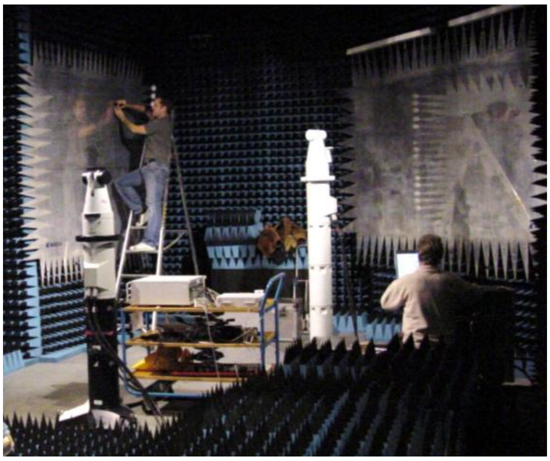

Figure 11 – Sampling the surface of the relocated subreflector by laser tracking of a hand-held target.

References

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[2] The measurements are performed by Introtech B.V., (www.introtech.nl)