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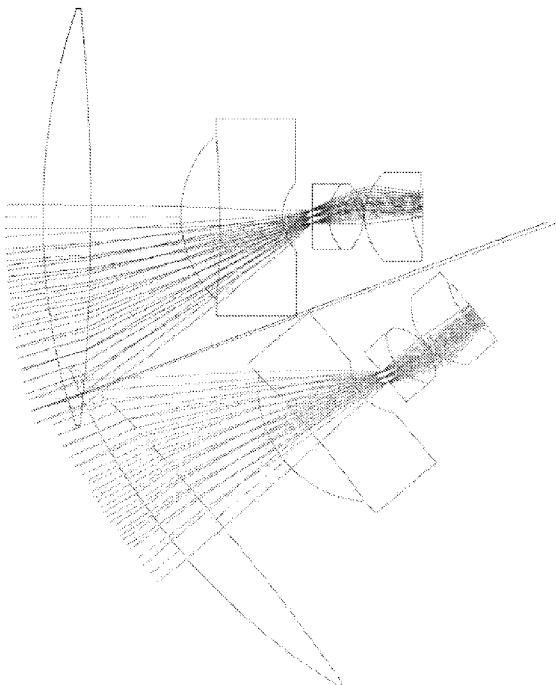
FIG. 12

(57) Abstract: A multicamera panoramic imaging system having no parallax. In an example, the multicamera panoramic imaging system includes multiple discrete, imaging systems disposed in a side-by- side array, wherein a field of view of each discrete, imaging systems is conjoined with a field of view of each adjacent discrete imaging system, further wherein a stencil of chief rays at the edge of the field of view of any one of the discrete imaging systems will be substantially parallel to a stencil of chief rays at the edge of the field of view of any adjacent ones of the discrete imaging systems such that all of the substantially parallel stencils of chief rays appear to converge to a common point when viewed from object space. A method for forming an image of an object having no parallax.

Imaging System, Method, and Applications

Related Application Data

The instant application claims priority to US provisional application No. 61/989,136 filed May 6, 2014, the subject matter of which is incorporated herein by reference in its entirety.

Background

Field of the Invention

Aspects and embodiments of the invention are most generally directed to an optical imaging system, methods pertaining thereto, and applications thereof; more particularly to a panoramic optical imaging system, methods pertaining thereto, and applications thereof; and, most particularly to a panoramic optical imaging system that has zero or substantially no parallax, methods pertaining thereto, and applications thereof.

Description of Related Art

Current 360 degree systems without parallax employ an arrangement of mirrors to scan the image and are limited by an imaging speed of 10 frames per second (fps). Google uses a 360 degree camera with refractive lenses developed by Immersive Media to capture photos for its Streetview software. The photos must be post-processed and corrected for parallax, costing time, which reduces Google's ability to scale its Streetview initiatives. Fisheye lenses provide wide angle imaging but at the cost of high distortion. Distortion is the physical result of mapping a large spherical object onto a small flat image plane.

Some companies have developed optical systems to simplify the process of taking a panoramic image. Rather than rotating the camera to get multiple shots, all of the photos are captured simultaneously with many cameras imaging different parts of the scene. Immersive Media and Greypoint Imaging have developed single shot 360 degree cameras that are available for varying price tags between $10,000 and $100,000. Both companies develop software to automatically correct for the artifacts (parallax) created in the image and offer a better solution than panoramas captured by one camera, e.g., the iPhone camera. The software, however, is not perfect and many artifacts still exist in the images. Anecdotally, Google, had one person carry a Dodeca 360 camera (offered by Immersive Media) around the Grand Canyon, and had to employ programmers to correct the images frame by frame for the artifacts induced by parallax.

Parallax and the Chief Rays of an optical system

Parallax is defined as "the effect whereby the position or direction of an object appears to differ when viewed from different positions, e.g., through the viewfinder and the lens of a camera." Parallax is created as a result of stitching together images from multiple cameras, each with its own unique perspective of the world.

Referring to Fig. 1, the chief ray of an optical system is the meridional ray that starts at the edge of an object, crosses the center of the optical axis at the aperture stop, and ends at the edge of the image at the detector. Thus the chief ray defines the size of an image.

The chief ray plays a critical role in the parallax created by stitching together multiple images. Fig. 2 illustrates two optical systems (cameras) side by side. For the lens unit on top, the square, triangle and rectangle are mapped to the same point in the image, whereas for the lens unit on bottom they are mapped to three distinct points as shown. In the top imaging system,

they are imaged by the same chief ray, whereas for the bottom imaging system, they are imaged by three distinct chief rays. When combining the two images in Fig. 3, parallax would occur and an image as shown in Fig. 4 would result.

The search for an algorithm that can correct for parallax has been going on for many years. Many solutions have been developed but even with the most sophisticated algorithms to date, artifacts are still left in panoramic images. For some, this may not be a problem as software engineers can be hired to fix the images frame by frame; however, for the general consumer this option of correcting each image is not feasible. A better solution is needed that effectively corrects for parallax before such a system can be made available to the consumer market. It is preferable to solve the problem of reducing parallax in an image optically, rather than computationally.

Current designs created for single shot panoramic imaging suffer from parallax because they are created from imaging systems with overlapping fields of view. Fig. 5 is taken from U.S. Patent 2,696,758. This figure illustrates how parallax is created in the 360 degree imaging systems available today. The field of views overlap and a triangle that appears at the edge of the FOV for the bottom lens system will appear at around 0.707 times the FOV in the imaging system on top. Thus, the triangle is mapped to different image points for each camera. On the bottom it is mapped to the full FOV (the edge of the image).

The inventor has thus recognized the advantages and benefits of a panoramic imaging system and associated methods in which there is no parallax, and where the parallax is eliminated optically rather than by post-processing software. Such a system would have applications including providing a scalable way to map the streets of the planet; allowing for the creation of virtual tours, both of cities and of private institutions; high frame-rate video

surveillance; military applications including drone and tank technology; an alternative for fisheye lenses which provide wide angle imaging at the cost of high distortion.

Brief Description of the Figures

Fig. 1 illustrates the chief ray of an optical system. The chief ray defines the height of the object as well as the height of the image.

Fig. 2 illustrates why parallax occurs when multiple refractive imaging systems are used to capture an image of a scene. In the lens unit on top, the three objects are mapped to the same image point; in the bottom lens unit they are mapped to three separate image points.

Fig. 3 (left) illustrates the image formed by the top lens unit in Fig. 2, whereas the image on the right is that formed by the bottom lens unit.

Fig. 4 shows the image that would result from combining the two images in Fig. 3.

Fig. 5 illustrates how parallax occurs in the cameras created today. The field of views overlaps and a triangle that appears at the edge of the FOV for the bottom lens system will appear at around 0.707 times the FOV in the imaging system on top. Thus, the triangle is mapped to different image points for each camera. On bottom it is mapped to the full FOV (the edge of the image).

Fig. 6 illustrates two imaging systems side by side which do not have parallax. The chief rays at the edge of each system are constrained to lie parallel one another. Thus, objects lying along this line are imaged to the same point in the image plane.

Fig. 7 illustrates the location of the non-parallax (NP) Point (as defined below) for both imaging systems shown.

Fig. 8 shows that the chief rays at the edge of the FOV are not parallel, thus the NP Points lie in different locations.

Fig. 9 illustrates an imaging system with NP Point lying before image sensor.

Fig. 10 illustrates two imaging systems aligned such that the chief rays at the edge of each ones FOV is parallel to the other.

Fig. 11 shows an imaging system with NP Point behind the image plane.

Fig. 12 shows a multiple unit imaging system with NP Points co-located.

Fig. 13 shows a 3-dimensional representation of a 360 degree lens system with edge rays constrained to lie along each dodecahedron face.

Fig. 14 shows a circle inscribed in a pentagon illustrating blind spots that would be created if lens was a circle rather than a pentagon.

Fig. 15 shows the first lens element of each system, initially designed to circumscribe regular pentagons.

Fig. 16: The diameter of the first lens element is constrained to be *1.7013a,* where *a* is the side length of the regular pentagon.

Fig. 17: The distance from the center of the first lens element to the center of the dodecahedron (NP Point) is *1.1135a* where *a* is the side length of the pentagon.

Fig. 18: The distance from the top of the pentagon face to the NP Point is constrained to be *1.31a* where *a* is the side length of the regular pentagon. Here the NP Point is the center of the dodecahedron.

Fig. 19: Diagram illustrating the constraints imposed on the first lens element with respect to the center of the dodecadron. "*a*" is the side length of each regular pentagon in the dodecahedron.

Fig. 20: Diagram illustrating that the maximal length of any element is constrained to fit within the 31.717 degree half angle cone of light emanating from the center of the dodecahedron.

Fig. 21: Three-dimensional representation of 1/12th of dodecahedron and angle between center of dodecahedron and center of pentagon edge.

Fig. 22: Three-dimensional representation of 1/12th of dodecahedron and angle between center of dodecahedron and edge of pentagon edge.

Fig. 23: Pentagon shaped lens element showing height to ray 1 and ray 37.

Fig. 24: Zemax diagram of current lens design showing Rays 1 and 37 in model.

Fig. 25: Three-dimensional Zemax diagram of current lens design from back.

Fig. 26: Three-dimensional Zemax diagram from side.

Summary

An aspect of the invention is a multicamera panoramic imaging system having no parallax. According to a non-limiting embodiment, the multicamera panoramic imaging system includes a plurality of discrete, imaging systems disposed in a side-by-side array, wherein a field of view of each discrete, imaging system is conjoined with a field of view of each adjacent discrete imaging system, further wherein a stencil of chief rays at the edge of the field of view of any one of the discrete imaging systems will be substantially parallel to a stencil of chief rays at the edge of the field of view of any adjacent ones of the discrete imaging systems such that all of the substantially parallel stencils of chief rays appear to converge to a common point when viewed from object space. In various non-limiting embodiments, the multicamera panoramic imaging system may include or be further characterized by the following features, limitations, characteristics either alone or in various combinations thereof:

-comprising a plurality of identical discrete imaging systems;

-wherein at least 50% of the stencil of chief rays deviate from parallel by twenty degrees or less;

-wherein each of the discrete imaging systems includes an image sensor, further wherein the apparent convergence point lies behind the image sensor of each of the discrete imaging systems;

-wherein none of the discrete imaging systems physically overlap;

-wherein the system has a dodecahedron geometry, further wherein the system is characterized by a 360 degree FOV;

-wherein a front lens of each of the discrete imaging systems is a portion of a single, contiguous freeform optic;

    -wherein each image sensor is a wavefront sensor;

-wherein each of the discrete imaging systems has a curved image plane so as to match a distortion and Petzval Curvature of the imaging system.

    An aspect of the invention is a method for forming an image of an object having no parallax. According to a non-limiting embodiment, the method includes providing a panoramic imaging system, wherein the panoramic imaging system comprises a plurality of discrete imaging systems each characterized by a field of view; and constraining a stencil of chief rays at the edge of the field of view of every one of the discrete imaging systems to be substantially parallel to a stencil of chief rays at the edge of the field of view of an immediately adjacent one of the discrete imaging systems such that all of the parallel stencils of chief rays appear to converge to a common point when viewed from object space, wherein the imaging system is parallax-free. In various non-limiting embodiments, the panoramic imaging method may include or be further characterized by the following features, limitations, characteristics, steps either alone or in various combinations thereof:

-further comprising constraining at least 50% of the stencil of chief rays to deviate from parallel by twenty degrees or less;

-further comprising using an algorithm to correct a distortion aberration in a contiguous 360 degree image formed by the imaging system.

An aspect of the invention is a method for designing a (substantially) parallax-free, panoramic imaging system. According to a non-limiting embodiment, the method includes determining an overall panoramic imaging system geometry, wherein the overall panoramic imaging system comprises a plurality of discrete, imaging systems having respective fields of view, disposed in a side-by-side array such that the fields of view of adjacent imaging systems conjoin; designing the discrete imaging systems such that a stencil of chief rays at the edge of the field of view of one of the discrete imaging systems will be substantially parallel to a stencil of chief rays at the edge of the field of view of an adjacent one of the discrete imaging systems such that the substantially parallel stencil of chief rays would appear to converge to a common point when viewed from object space. In various non-limiting embodiments, the panoramic imaging method may include or be further characterized by the following features, limitations, characteristics, steps either alone or in various combinations thereof:

-wherein the overall panoramic imaging system comprises a plurality of identical discrete imaging systems;

-wherein in designing the discrete imaging systems, ensuring that there is no physical overlap between any of the plurality of the discrete imaging systems;

-wherein in designing the discrete imaging systems, ensuring that the apparent convergence point lies behind a respective image sensor of each discrete imaging system.

Detailed Description of Exemplary, Non-limiting Embodiments

For a panoramic camera to achieve minimal parallax, the field of views (FOV) of the imaging systems must not overlap. Thus, the chief ray at the edge of the FOV must approach the optical system parallel to the chief rays at the edge of the adjacent optical system.

Fig. 6 illustrates two imaging systems side by side which do not have parallax. The chief rays at the edge of each system are constrained to lie parallel one another. Thus, objects lying along this line are imaged to the same point in the image plane. This is an approach that can be used to design the individual lens elements. The fields of view do not overlap one another because the chief rays at the blending angles are constrained to be parallel to one another and converge to a common point. The common point will depend on the geometry in which the lenses are encased. In other words, the chief rays are constrained to be parallel such that they appear to cross the optical axis at the same point when viewing the lens system from object space. In actuality, they cross the optical axis at an image sensor, which lies before this imaginary point, but it appears, looking into the lens system from object space, that they cross at the same point.

NP Point (No Parallax Point)

To aid in the understanding of the previous concept, we define a term referred to as the *No Parallax Point (NP Point)*. The NP Point is an abstraction used for understanding how the chief rays at the edge of the FOV can physically be made to lie parallel to one another and what rules they should follow. The *NP Point* is the point where the chief rays at the edge of adjacent optical systems intersect the optical axis when viewing the system from object space for a panoramic imaging system without parallax.

According to the embodied invention, the NP Points for each imaging system must lie in the same location. That is to say, that the rays of adjacent optical systems must be parallel. Fig. 9 shows an imaging system with the NP Point lying in front of the imaging sensor. Fig. 10 illustrates two imaging systems aligned such that the chief rays at the edge of each one's FOV is parallel to the other. This constraint means that the NP Point must be at the same location for both systems. When the NP Point is in front of the image sensor, it is impossible to align the NP Points without the lens elements overlapping. This system would not have any parallax, but it is physically impossible to implement. This indicates that when designing the optical system, the NP Point should lie behind all of the elements in the imaging system so that no elements physically overlap with one another.

Fig. 11 shows a system where the NP Point lies behind the image plane. When this is the case, it is possible to arrange multiple imaging systems such that the fields of view do not overlap, as shown in Fig. 12. The exact location of the NP Point will be determined by the geometry of the lens arrangements. By arbitrarily picking a location, that is to say arbitrarily choosing a ray height and incident angle such that the chief ray appears to cross the optical axis behind the image plane, the geometry of lens systems may require hundreds of lens units to capture a full 360 degree image. The NP Point location must be determined after considering the geometry one may wish to use for the lenses.

An embodiment of the present invention relates to a multicamera panoramic imaging system, where the fields of adjacent imaging units merge to form the composite field of view of the entire imaging system, as illustrated in the schematic of Fig. 7. Traditional panoramic imaging systems put together imaging units in such a way that their respective fields of view

overlap as illustrated in the schematic of Fig. 8, which leads to parallax in the resulting images, and requires corrective software to stitch the images together to remove the parallax.

In the instant exemplary embodiment, the rays striking the edge of one imaging unit are constrained to lie parallel to the incoming rays of an adjacent imaging unit so that both imaging systems share the same set of edge rays. As seen in the 3-dimensional model of Fig. 13, the rays at the edge of one imaging unit are the same as those at the edge of an adjacent imaging unit. The rays are the gray lines constrained to lie along the surface of the dodecahedron edge. The gray rays at the edge of each pentagon shaped lens are coincident to the rays entering its neighboring surface. All rays at radii beneath the edge rays lie at smaller angles of incidence so that these rays do not overlap rays from adjacent systems.

The embodied panoramic imaging system utilizes the aforementioned technique of designing an imaging system with a NP point behind the image sensor, and combines multiple lens systems in a dodecahedron geometry, to create a 360 degree FOV camera with minimal or no parallax.

The first lens element will be shaped into the surface of a regular pentagon. The complete system will be composed of 12 discrete imaging units, each with a common NP point for rays along the edge of the pentagon and constrained to have incident angles meeting the geometry specified by that of a dodecahedron.

A dodecahedron is a polyhedron with 12 surfaces. A polyhedron is a three dimensional solid consisting of a collection of polygons joined at the edges. Each side of the dodecahedron is a regular pentagon (a pentagon with equal length sides). Dodecahedrons have some important geometrical properties that must be understood in order to design a lens system utilizing the

geometry. The properties will be discussed in turn next after briefly discussing why the first lens must be shaped into the surface of a pentagon.

By using a circularly edged lens as the first element in the dodecahedron geometry, it is not possible to capture all information in the 360 degree field of view using the current technique of aligning edge rays. The missing area from where the first lens is inscribed in the pentagon (shaded region in Fig. 14) creates blind spots. Because the fields of view never overlap, this information is never captured. It can be calculated that the ratio between the area of a circle to the area of a pentagon it is inscribed in is equal to $\pi/5$ or 62.83%. This is the maximal amount of information that we can record for the 360 degree field around us. Blind spots created between the lens and the pentagon delete nearly 40% of information in the 360 degree image.

The following description is meant to illustrate the geometry of a dodecahedron and is necessary when creating a lens system utilizing the aforementioned NP technique and a dodecahedron geometry, but is not essential for the purposes of creating the no parallax, panoramic imaging system embodied herein.

Property 1: Diameter of circle circumscribing regular pentagon

For each of the 12 individual lens systems, the first lens will be designed such that it circumscribes each of the regular pentagons of the dodecahedron as shown in Fig. 15. The diameter of a circle circumscribing a regular pentagon is:

$$D = a/sin\ (36°) = 1.7013a$$

In the equation above, "*a*" is the side length of the regular pentagon. The first lens element of each system will fully circumscribe each pentagon and so the diameter of the first lens element for each system is given as *1.7013a* as illustrated in Fig. 16.

Property 2: Inscribed sphere touching center of each pentagon

The radius of an inscribed sphere (tangent to each of the dodecahedron's faces) is:

$$r_i = a\frac{1}{2}\sqrt{\frac{5}{2} + \frac{11}{10}\sqrt{5}} \approx 1.113516364 \cdot a$$

This radius is the distance from the center of the dodecahedron, which will be the NP Point for each lens in this design, and the center of the pentagon's face, which coincides with the center (optical axis) of the first lens element in a system occupying that pentagon. This point is at the center of each pentagon face. The length between the NP point and the center of the dodecahedron is constrained to be *1.1135a* where *a* is the length of one of the pentagon sides, as illustrated in Fig. 17.

Property 3: Mid-radius of Dodecahedron

The mid-radius is the point connecting the center of the dodecahedron and the middle of each edge. This length is given as follows:

$$r_m = a\frac{1}{4}\left(3 + \sqrt{5}\right) \approx 1.309016994 \cdot a$$

This equation constrains the distance between the top of the pentagon face and the NP Point, as illustrated in Fig. 18.

Constraints

The geometric properties of a dodecahedron constrain the design of the 12 lenses that will embody it. In particular, we have the following four parameters based upon the description given above:

1.   Diameter of 1st lens element: 1.7013a;

2.   Distance from 1st lens element to center of dodecahedron: 1.1135a;

3.   Distance from top of 1st lens element to center of dodecahedron: 1.31a;

4.   FOV = 37.3777 degrees

Given any two of the first three constraints, we have that the angle between the optical axis of the lens and the top of the first lens element is 37.3777 degrees (see Fig. 19):

$$\tan^{-1}((1.7013/2)/1.1135) - 37.377°.$$

We want this angle of 37.37 degrees to be the field of view of the lens. This will ensure that the NP Point, that is the point where the chief ray of the blending (the blending angle being the full FOV) intersects the optical axis in object space, lies at the center of the dodecahedron. All of the other constraints will ensure that the lens elements lie before the NP Point and that the elements fall within the 31.717 degree half angle cone of light.

Diameter of Other Lens Elements and Sensor

With the four constraints given above, we know what the size of each lens element after the first must be in order to fit into the dodecahedron geometry. In order for the preceding lens elements to fit, any lens or sensor element must fit inside of the 31.717 degree cone of light beginning at the center of the dodecahedron and tangential to the diameter of the first lens element. As the distance from the first lens element increases, the diameter of the preceding lens elements will decrease proportionally (see Fig. 20).

The maximum diameter of any lens element or sensor preceding the first can be found geometrically to be less than or equal to *(1.1135a – D)*tan (31.716 degrees)* where *D* is the distance of that element from the first lens element.

Thus, we now have the five constraints that will allow this lens system to match the geometry of a dodecahedron and permit 360 degree imaging:

1.   Diameter of 1st lens element: *1.3763a*;

2.   Distance from 1st lens element to center of dodecahedron: *1.1135a*;

3.   Distance from top of 1st lens element to center of dodecahedron: *1.31a*;

4.   FOV = 37.377 degrees;

5. $\varphi_{Li} < (1.1135a - D_{L1, Li})$ tan (31.717°),

where φ_{Li} is the diameter of any lens element separated by a distance $D_{L1, Li}$ from the first. Given the above five constraints, where all lenses are designed such that they fall within the 31.717 degree cone of light emanating from the center of the dodecahedron, it is possible to construct a lens system without parallax.

System Design

A geometry for the lenses was chosen. Platonic solids have the property that they are composed of many solids of equal geometry and volume. For a system imaging 360 degrees, this allows the composite imaging system to be made from the same replicated lens design. A dodecahedron geometry was chosen because it is approximately spherical in its geometry.

In order for the edge rays of one imaging unit to lie parallel to those of an adjacent unit, they must enter at the same angle. The angle shared by both imaging units is that of the dodecahedrons edge surface. At the center of the edge surface, the angle with respect to the center of the dodecahedron center is 31.717 degrees, as illustrated in Fig. 21. At the corner of the edge surface, the angle with respect to the center of the dodecahedron center is 37.377 degrees, as illustrated in Fig. 22.

In order to make the rays along adjacent imaging units match, the first lens of the imaging unit is cut into a pentagon, matching the surface of the dodecahedron. At the center of the edge, the ray striking the surface enters with an angle of incidence of 31.717 degrees. At the corner of the edge, the angle of incidence of an entering ray is 37.377 degrees. At all points

along the edge of the lens, the angle of incidence of an entering ray is made to match the geometry of the dodecahedron surface.

The angle of incidence for 37 rays along the edge of the pentagon lens was calculated using trigonometry, knowing the distance from the center of the dodecahedron to the center of the pentagon face, and knowing the distance from the center of the dodecahedron to the edge point in question as shown in the figures 21 and 22. The height of each ray was constrained to lie along the pentagon edge. For example, with a radius of 120 mm describing the circumscribed circle of surface 1, the ray at point 1 has a height of 48.54 mm and an angle of incidence of 31.717 degrees. The ray at point 37 has a height of 60 mm and an angle of incidence of 37.377 degrees. Table I describes the values for ray heights and angle of incidence for 37 points between Point 1 and Point 36 in Fig. 23.

Table I
(Data showing constraints on 37 rays lying along the edge of the first lens)

Point	Ray Height	Angle of Incidence
1	-48.54101966	31.71747441
2	-48.55131914	31.72137741
3	-48.58220446	31.7330904
4	-48.6336364	31.75262531
5	-48.70554989	31.78000204
6	-48.79785436	31.81524851
7	-48.91043437	31.8584007
8	-49.04315028	31.90950275
9	-49.19583915	31.96860698
10	-49.36831565	32.03577404
11	-49.56037318	32.111073
12	-49.77178508	32.19458149
13	-50.00230585	32.28638584
14	-50.25167251	32.38658121
15	-50.51960599	32.49527181
16	-50.80581256	32.61257109
17	-51.10998523	32.7386019
18	-51.43180524	32.87349676

19	-51.77094349	33.01739809
20	-52.12706197	33.17045845
21	-52.49981514	33.33284086
22	-52.88885128	33.50471903
23	-53.2938138	33.68627773
24	-53.7143425	33.87771306
25	-54.1500747	34.07923284
26	-54.60064642	34.29105695
27	-55.0656934	34.51341771
28	-55.54485206	34.74656026
29	-56.03776039	34.99074298
30	-56.54405884	35.2462379
31	-57.06339098	35.51333115
32	-57.59540424	35.7923234
33	-58.13975051	36.0835303
34	-58.69608667	36.38728295
35	-59.26407504	36.70392839
36	-59.84338384	37.03383003
37	-60	37.37736813

A diagram illustrating the ray constraints is shown in Fig. 24. Ray 1 has a height of 48.54 mm and an angle of incidence of 31.717 degrees. Ray 1 is the ray going through point 1 in Fig. 24. Ray 2 has a height of 60 mm and an angle of incidence of 37.377 degrees and is the ray going through point 37 in Fig. 24. All 37 rays are constrained by the ray heights and angles specified in the table above. Constrained in this way, all rays enter the lens at the same angle as the surface of the dodecahedron. Looking at those same rays in another way, we can see that the rays are constrained properly to a pentagon geometry at the correct angles of incidence, as illustrated in Figs. 25 and 26.

I claim:

1.   A method for forming an image of an object, comprising:

        providing a panoramic imaging system, wherein the panoramic imaging system comprises a plurality of discrete imaging systems each characterized by a field of view; and

        constraining a stencil of chief rays at the edge of the field of view of every one of the discrete imaging systems to be substantially parallel to a stencil of chief rays at the edge of the field of view of an immediately adjacent one of the discrete imaging systems such that all of the parallel stencils of chief rays appear to converge to a common point when viewed from object space,

        wherein the imaging system is parallax-free.

2.   The method of claim 1, further comprising constraining at least 50% of the stencil of chief rays to deviate from parallel by twenty degrees or less.

3.   A method for designing a (substantially) parallax-free, panoramic imaging system, comprising:

        determining an overall panoramic imaging system geometry, wherein the overall panoramic imaging system comprises a plurality of discrete, imaging systems having respective fields of view, disposed in a side-by-side array such that the fields of view of adjacent imaging systems conjoin;

        designing the discrete imaging systems such that a stencil of chief rays at the edge of the field of view of one of the discrete imaging systems will be substantially parallel to a stencil of chief rays at the edge of the field of view of an adjacent one of the discrete

imaging systems such that the substantially parallel stencil of chief rays would appear to converge to a common point when viewed from object space.

4.   The design method of 3, wherein the overall panoramic imaging system comprises a plurality of identical discrete imaging systems.

5.   The method of claim 3, wherein in designing the discrete imaging systems, ensuring that there is no physical overlap between any of the plurality of the discrete imaging systems.

6.   The method of claim 3, wherein in designing the discrete imaging systems, ensuring that the apparent convergence point lies behind a respective image sensor of each discrete imaging system.

7.   A multicamera panoramic imaging system, comprising:

a plurality of discrete, imaging systems disposed in a side-by-side array, wherein a field of view of each discrete, imaging systems is conjoined with a field of view of each adjacent discrete imaging system, further wherein a stencil of chief rays at the edge of the field of view of any one of the discrete imaging systems will be substantially parallel to a stencil of chief rays at the edge of the field of view of any adjacent ones of the discrete imaging systems such that all of the substantially parallel stencils of chief rays appear to converge to a common point when viewed from object space.

8.   The multicamera panoramic imaging system of claim 7, comprising a plurality of identical discrete imaging systems.

9.   The multicamera panoramic imaging system of claim 7, wherein at least 50% of the stencil of chief rays deviate from parallel by twenty degrees or less.

10.   The multicamera panoramic imaging system of claim 7, wherein each of the discrete imaging systems includes an image sensor, further wherein the apparent convergence point lies behind the image sensor of each of the discrete imaging systems.

11.   The multicamera panoramic imaging system of claim 7, wherein none of the discrete imaging systems physically overlap.

12.   The multicamera panoramic imaging system of claim 7, wherein the system has a dodecahedron geometry, further wherein the system is characterized by a 360 degree FOV.

13.   The multicamera panoramic imaging system of claim 7, wherein a front lens of each of the discrete imaging systems is a portion of a single, contiguous freeform optic.

14.   The multicamera panoramic imaging system of claim 10, wherein each image sensor is a wavefront sensor.

15.   The multicamera panoramic imaging system of claim 7, wherein each of the discrete imaging systems has a curved image plane so as to match a distortion and Petzval Curvature of the imaging system.

16.   The method of claims 1 or 3, further comprising using an algorithm to correct a distortion aberration in a contiguous 360 degree image formed by the imaging system.

Marginal Ray

Chief Ray

Aperture Stop
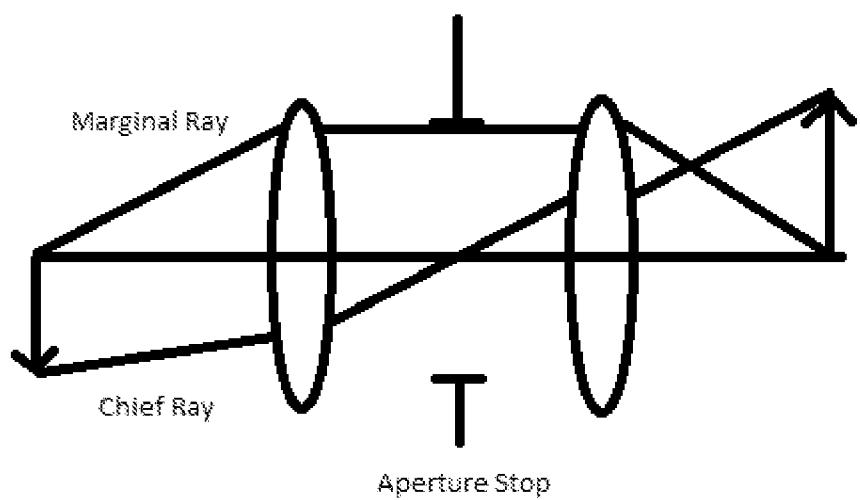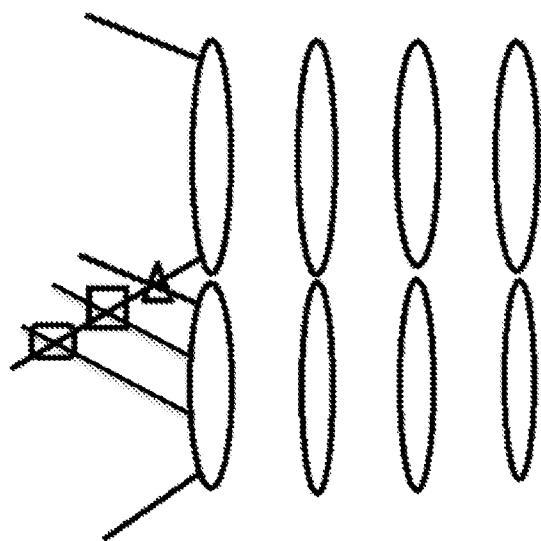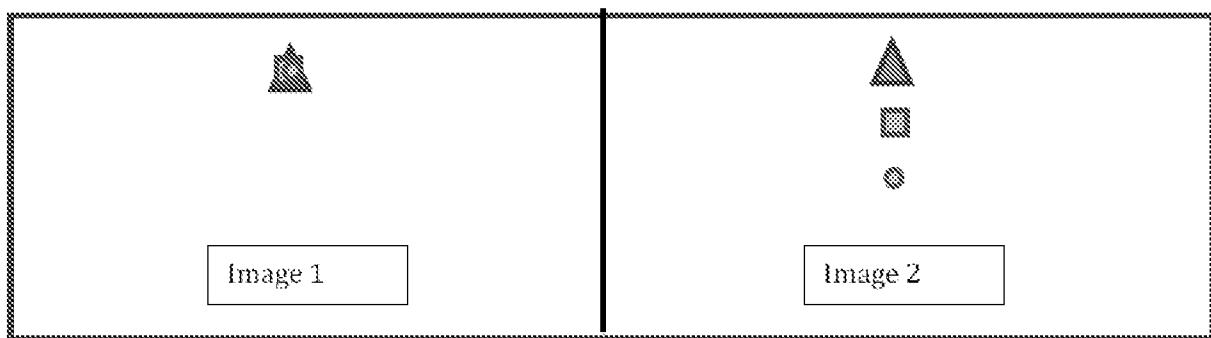
FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

NP Point
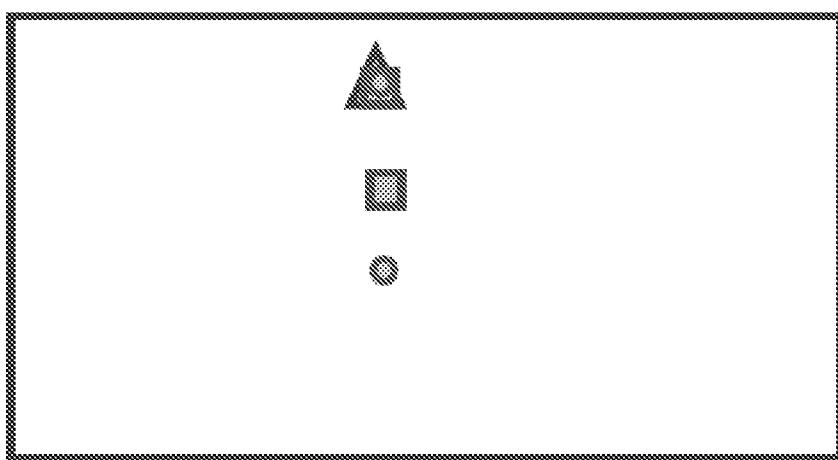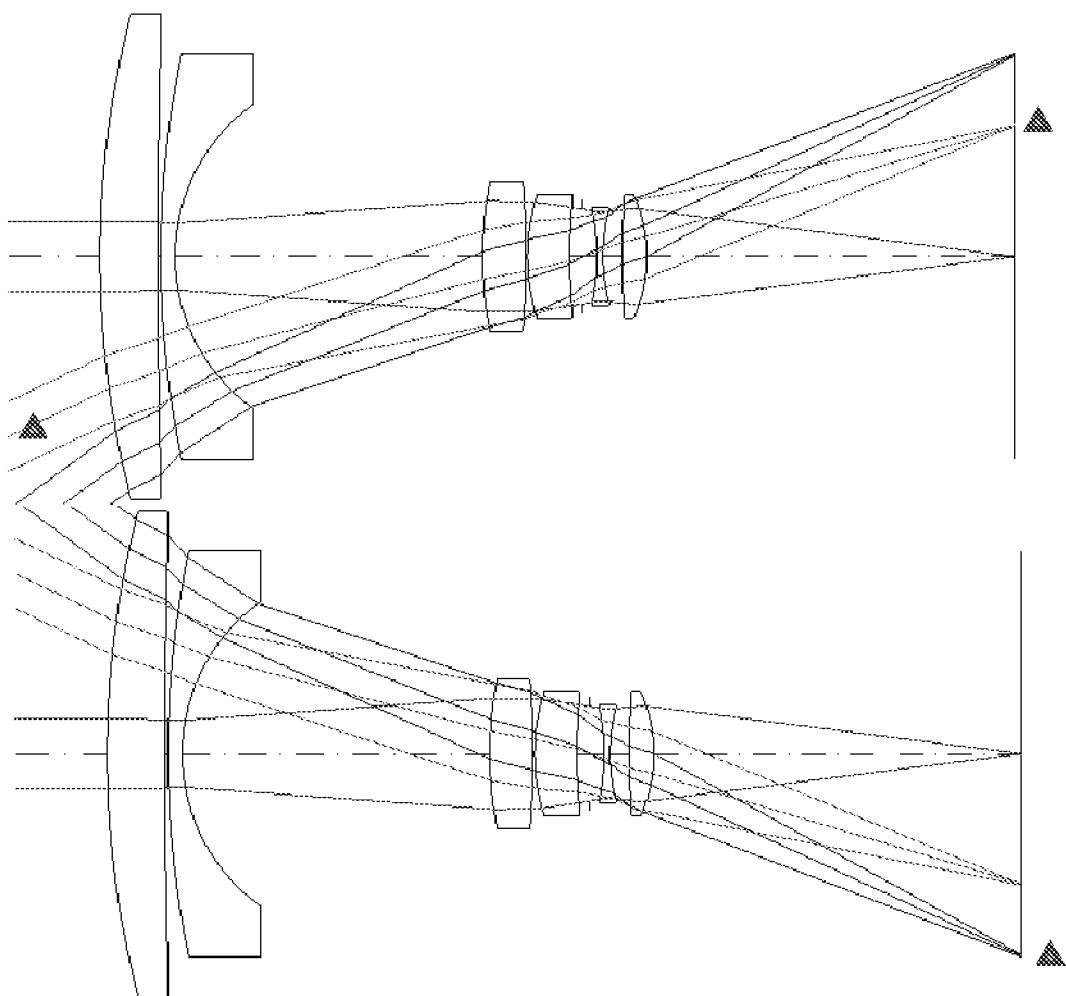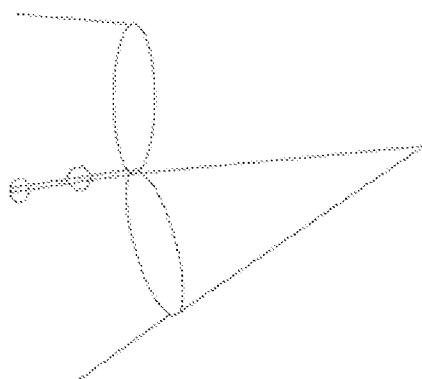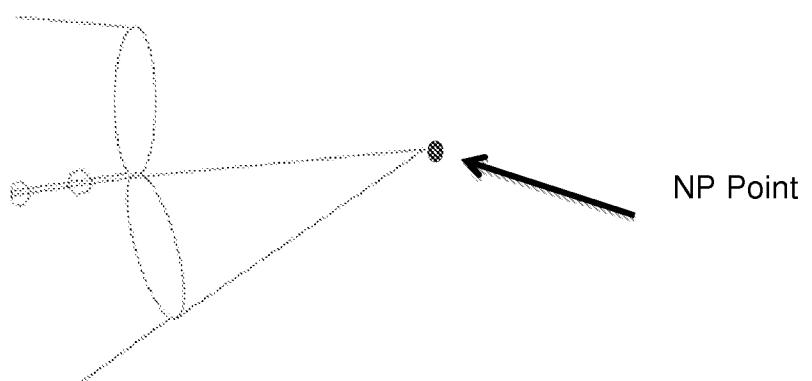
FIG. 7
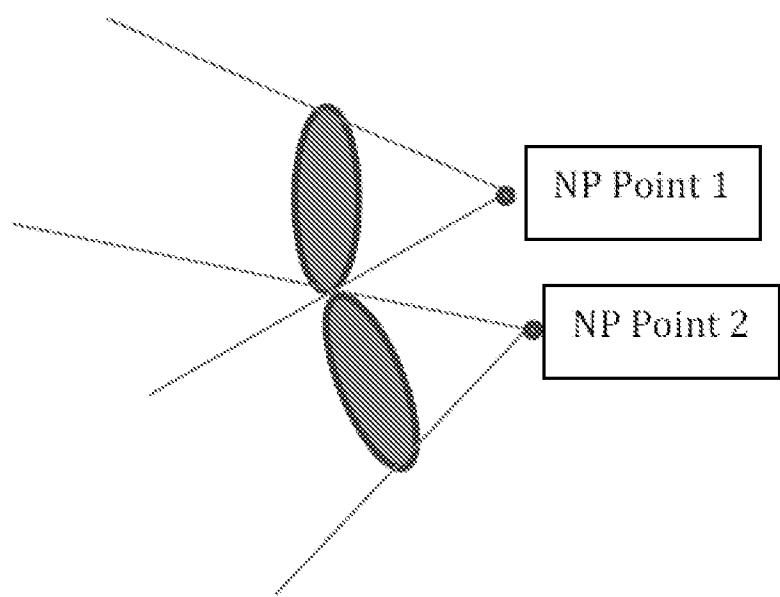
FIG. 8
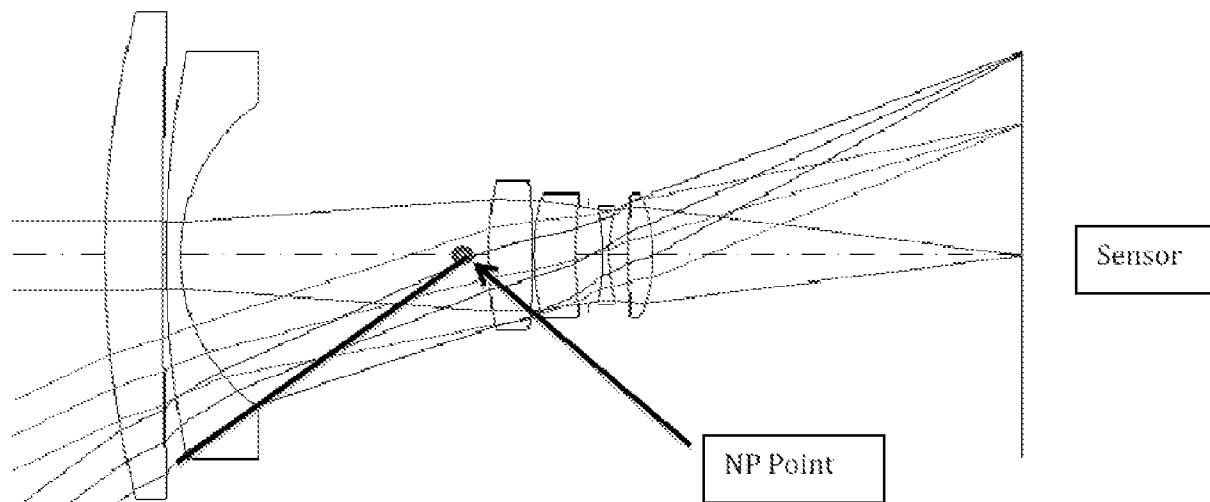
FIG. 9
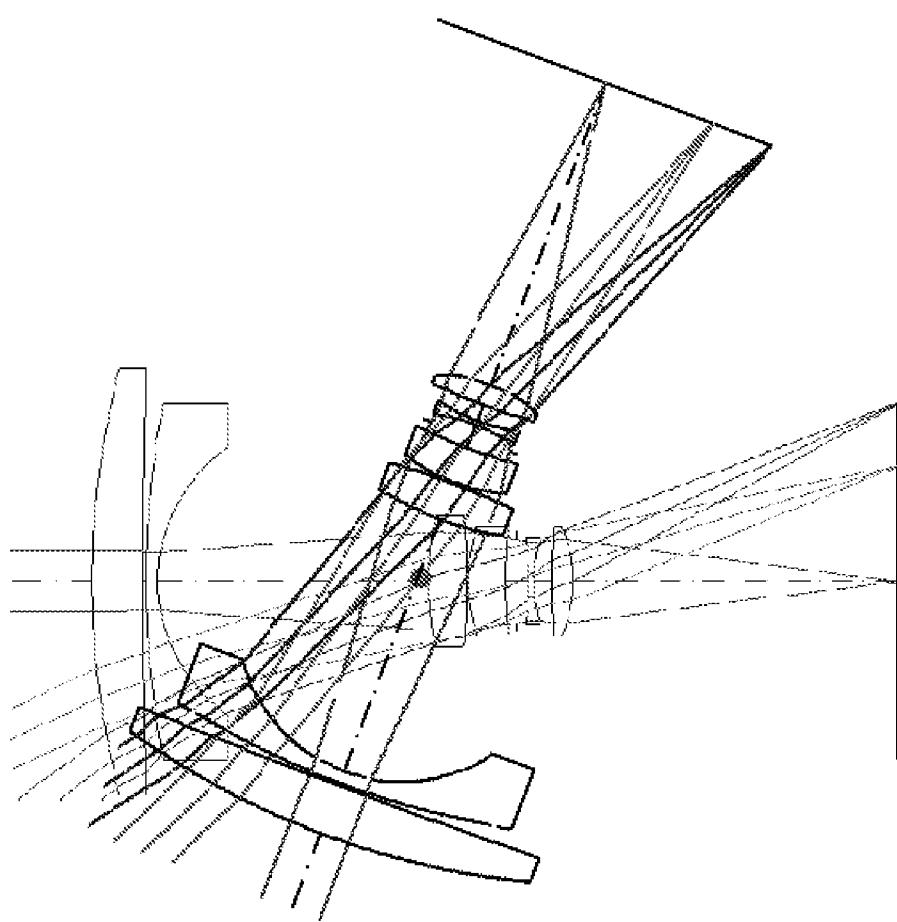
FIG. 10
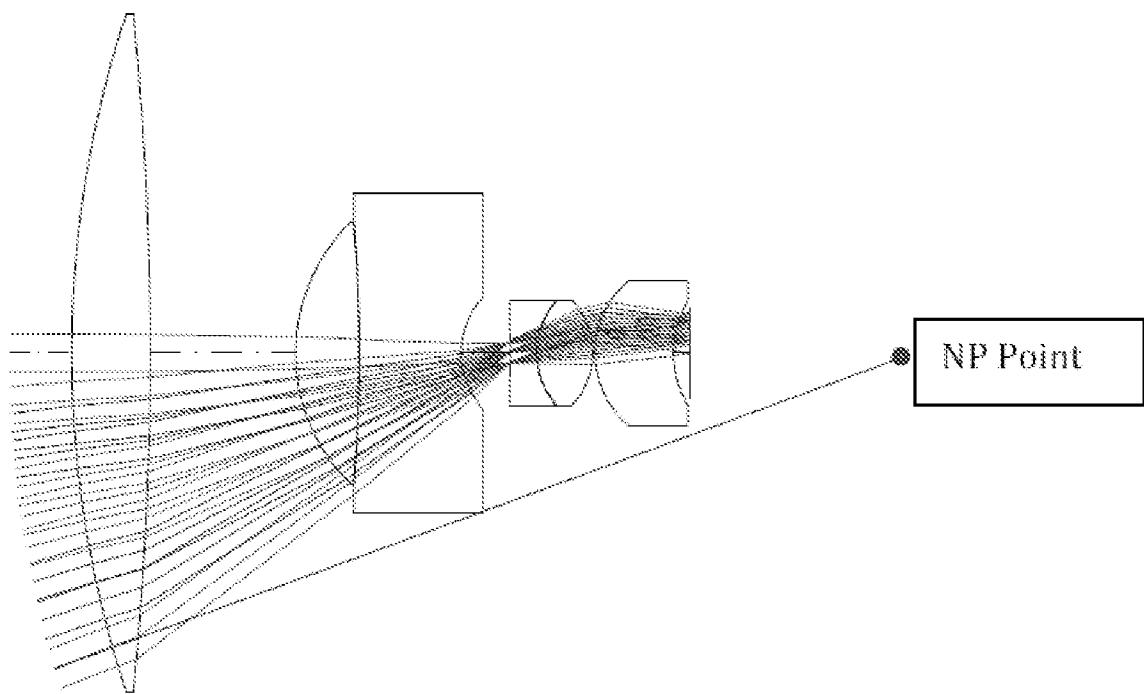
FIG. 11
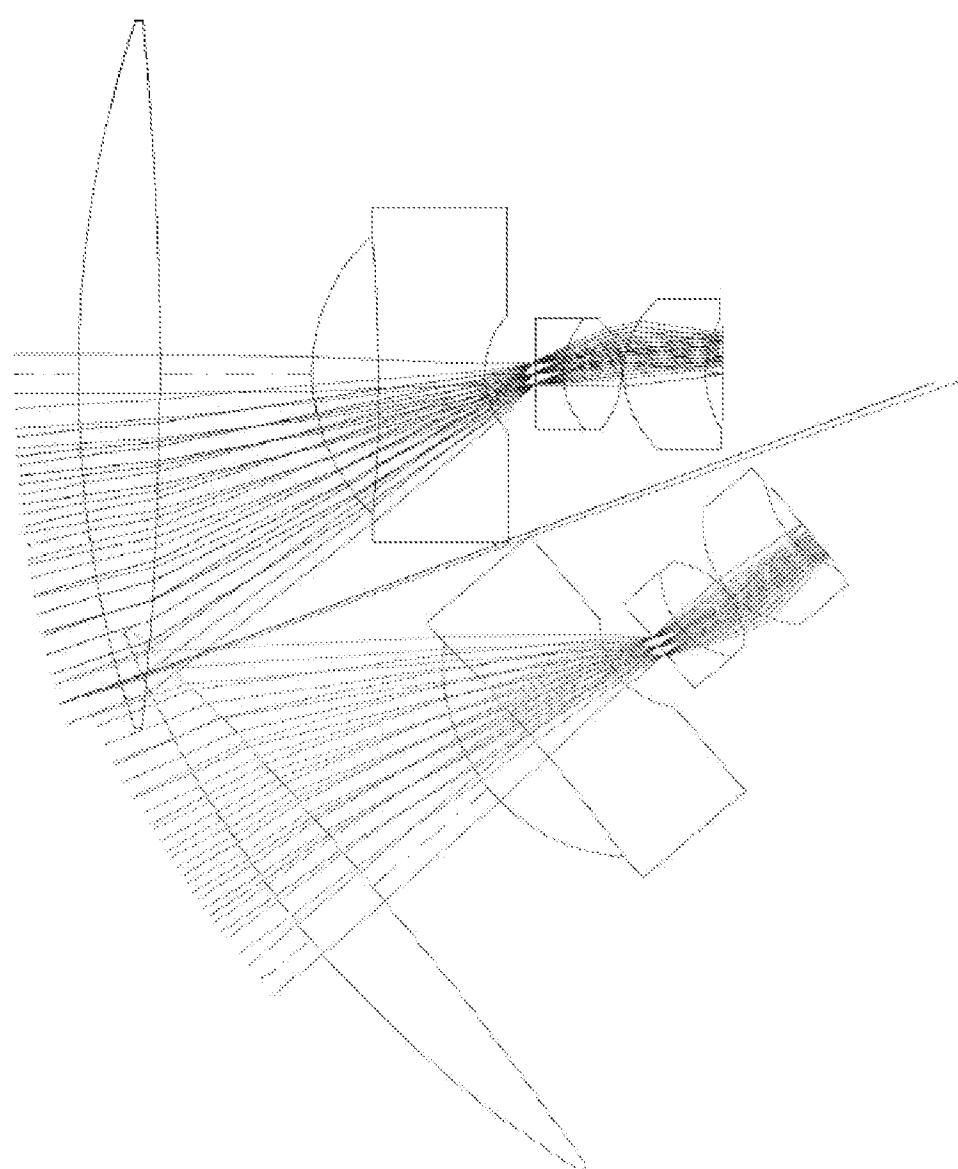
FIG. 12

FIG. 13

FIG. 14

FIG. 15

1.7013

NP

FIG. 16

NP

1.1135a
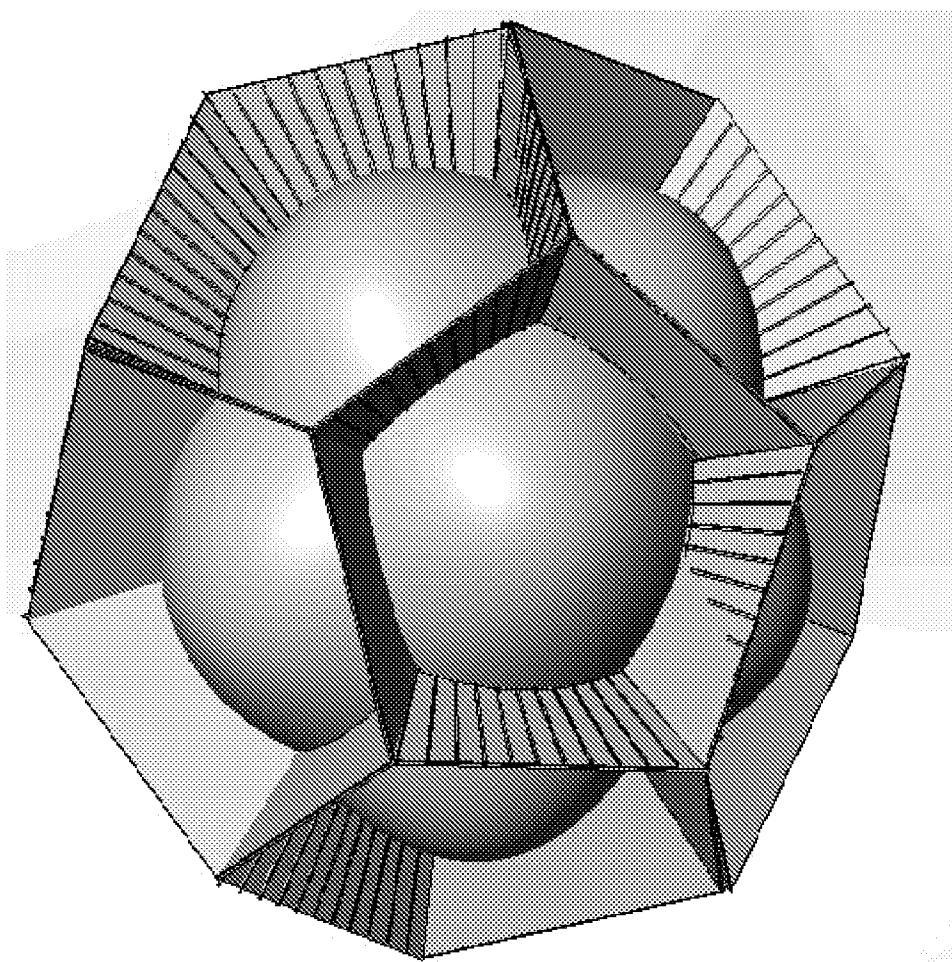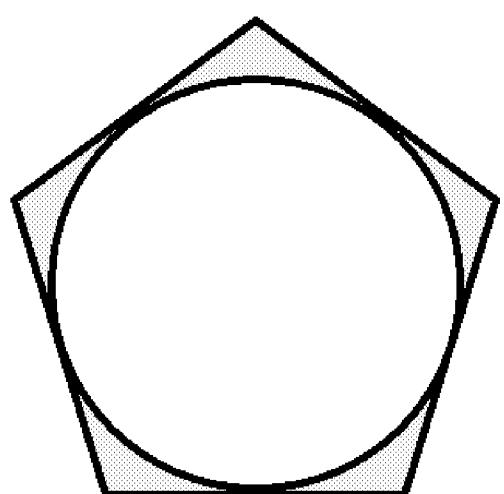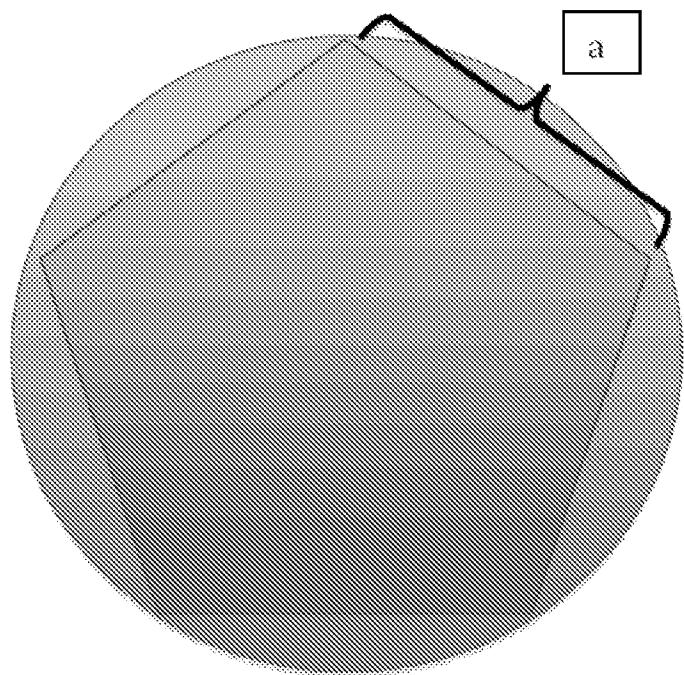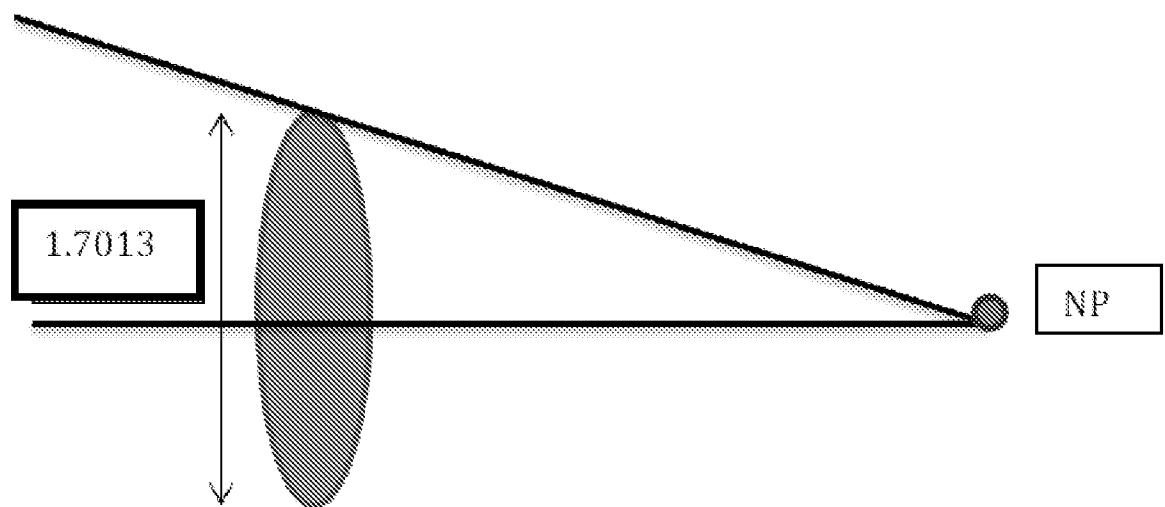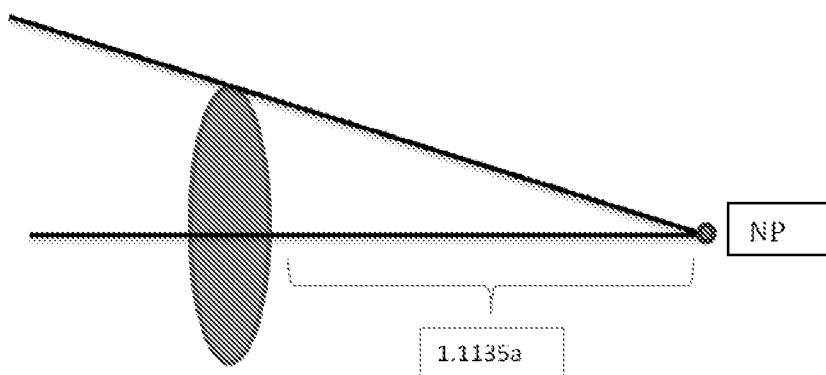
FIG. 17
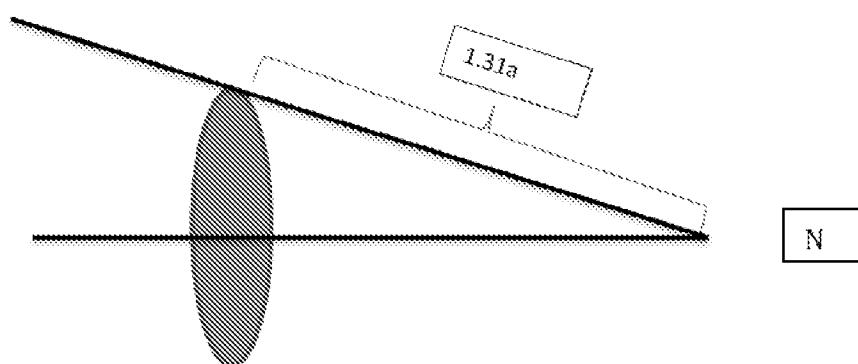
FIG. 18
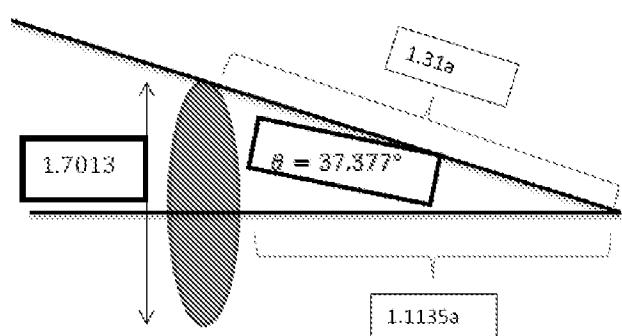
FIG. 19
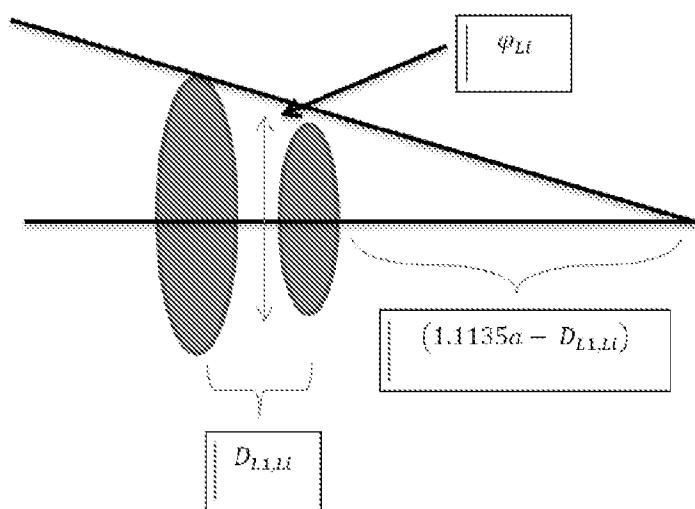
FIG. 20
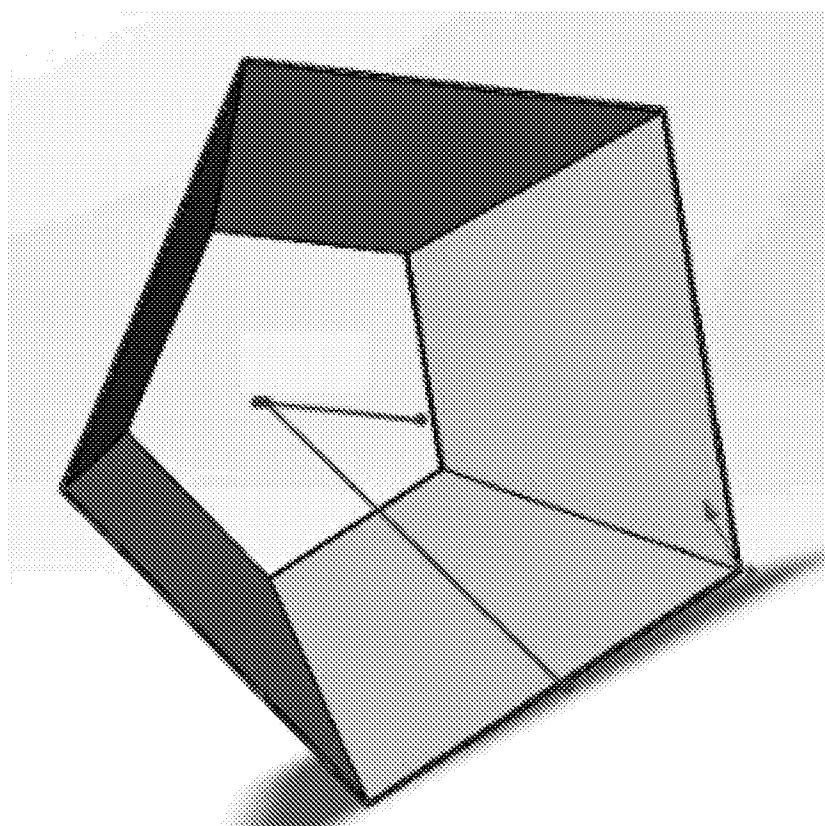
$\theta = 31.717°$

FIG. 21

$\theta = 37.377°$

FIG. 22

60 mm

48.54 mm

Point 1   Point 37
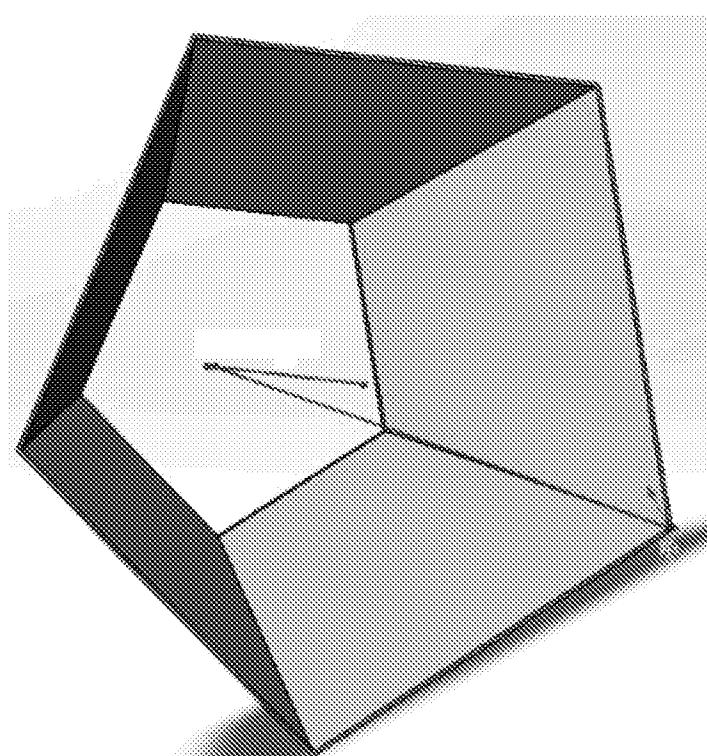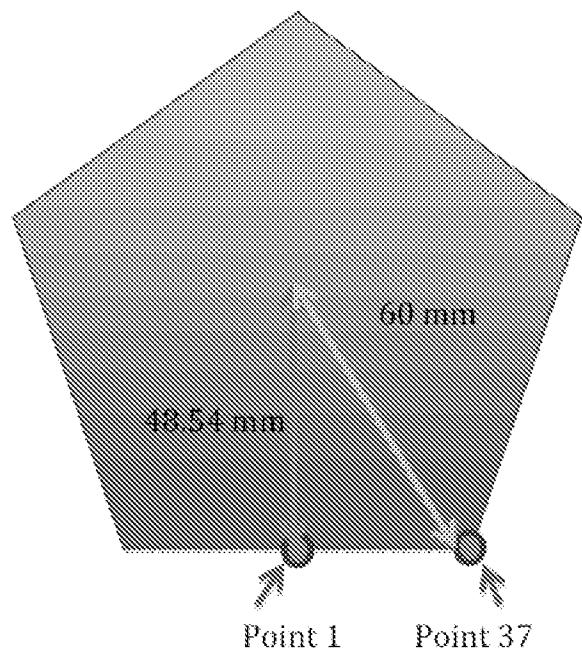
FIG. 23
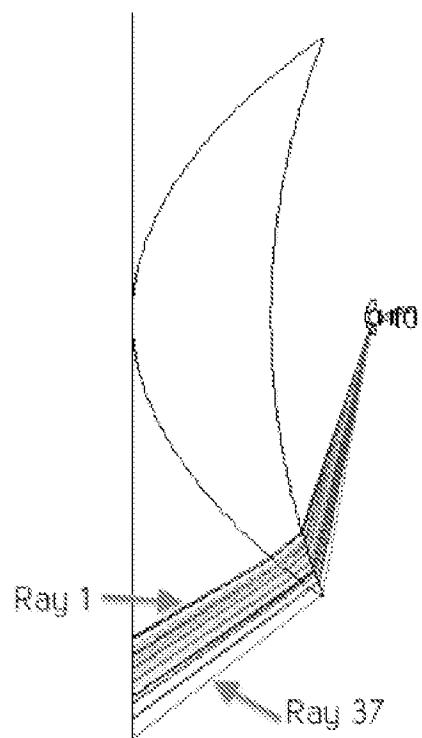
FIG. 24
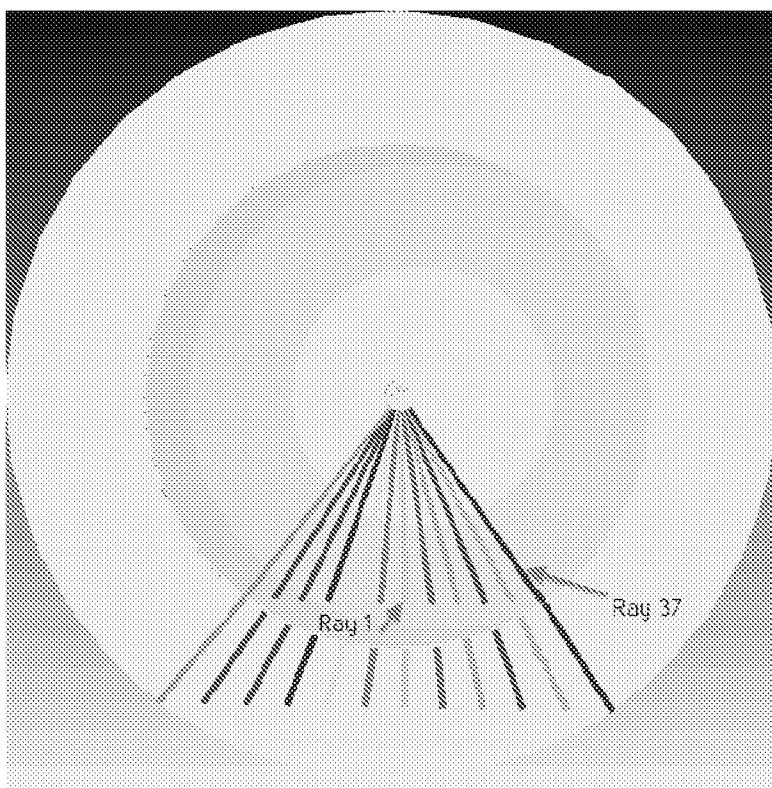
FIG. 25

FIG. 26

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B13/06   G03B37/04   H04N5/232
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02B   G03B   H04N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 593 999 A1 (SONY CORP [JP]) 9 November 2005 (2005-11-09)	1-14,16
Y	figures 1,2 paragraph [0015] paragraph [0004]	15
X	US 2004/051805 A1 (YOSHIKAWA KOICHI [JP] ET AL) 18 March 2004 (2004-03-18) figures 4,5 paragraph [0049] - paragraph [0053] paragraph [0029] - paragraph [0031]; figure 2	1,3-7, 10-12
Y	US 2013/076900 A1 (MROZEK FRED [US] ET AL) 28 March 2013 (2013-03-28) paragraph [0059]	15

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

* Special categories of cited documents :

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 July 2015	14/07/2015

Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Linke, Felix

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Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

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			US	2013076900 A1	28-03-2013
			WO	2013043215 A1	28-03-2013