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Extended retroreflector insensitive to tube bend

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Abstract

Boresighting of laterally separated optical systems or lines of sight may require the lateral transfer of a collimated alignment beam without the introduction of error into the look angle represented by the alignment beam. An extended retro of some sort (e.g., cube corner) is commonly used for transfer of the look angle reference. One major error source that degrades the accuracy of the extended retro is bending of the "tube" connecting the retroreflector input and output optics. Control of this bending requires that the retroreflector be well isolated from environmental stress such as vibration or thermal gradients across the tube. Alternatively, the bend of the tube may be monitored. This paper describes some of the techniques used in the accurate lateral transfer of alignment beams. Several approaches which are functionally equivalent to an extended retroreflector are discussed. The five-surface retroreflector concept (using empty pentaprisms) is modified into an "Alignment Reference Transfer System" (ARTS), which to first order is insensitive to tube bends. Several optical configurations of the ARTS concept are shown, and the tradeoffs leading to the selection of the baseline design are described. The error sources in the baseline are pointed out. The coupling of ARTS input beam misalignment to tube bend produces an ARTS error which is the product of the two. A brief discussion of the application of the ARTS in the boresight of two apertures is also included.

Introduction

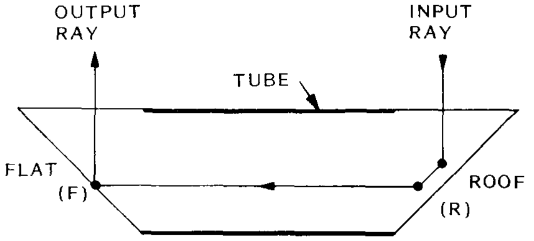
The alignment of separate optical systems or elements often requires the establishment of a common look angle reference to which the look angles of the individual systems can be compared. Typically, the look angle refrence is an alignment beam generated along the surface normal of a reference flat mirror and laterally transferred through a periscope or retroreflector to an appropriate position relative to the system to be aligned. In space systems, which require high accuracies of boresight and alignment between elements that are physically separated by distances on the order of meters, the physical stability of the lateral transfer system itself becomes a limiting factor in the achievable accuracy.

Concepts for lateral transfer of alignment beams

Besides a periscope, the most commonly used concept for the lateral transfer of an alignment beam is an extended cube corner. This concept, shown in Figure 1, is a three-surface retro consisting of a 90-degree roof and a flat mirror connected by a tube. Although it is a simple system, the extended cube corner is sensitive to tube bends both in-plane (in the plane defined by the input and output beams) and out-of-plane, as well as tube twist. (All the concepts to follow are sensitive to tube twist, which must be absent or monitored.) The first-order sensitivity of the cube corner to tube bend requires that the tube be thermally and structurally isolated to prevent thermal gradients and vibrations from degrading the accuracy of the transferred alignment beam.

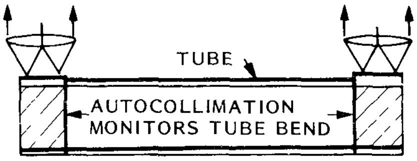
The alignment rod shown in Figure 2 is a rigid structure which functionally serves as a lateral transfer system. In the alignment rod concept, reference flats on the ends of the rod serve as nominally parallel look angle references to which the systems to be aligned can be autocollimated. The alignment rod is sensitive in first order to in-plane tube bend and tube twist. Out-of-plane tube bend has no effect. In-plane tube bend can be conveniently monitored by in-tube autocollimation. Although the alignment rod is less susceptible to tube bend and capable of self monitoring, it is a relatively complicated configuration requiring at least two separate alignment beams and autocollimators (three if self monitoring is desired).

The pentaprism retroreflector, a five-surface retro shown in Figure 3, is conceptually constructed by connecting an ordinary pentaprism and a roof pentaprism with a tube. It is a concept which combines the simplicity of an extended cube corner or periscope with the single axis tube bend sensitivity of the alignment rod. This configuration is sensitive to tube twist and out-of-plane tube bend but is to first order insensitive to in-plane tube bend. One interesting feature of the pentaprism retroreflector is that bending the tube ends into the plane of Figure 3 will produce a first order angular shift in the output



- SENSITIVE TO TUBE TWIST, 2X IN-FIGURE BEND
OUT-OF-FIGURE BEND

Figure 1. Extended cube corner.

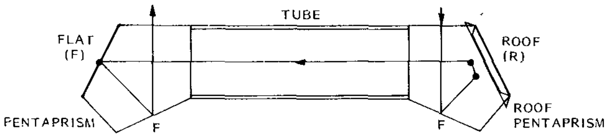


- SENSITIVE TO TUBE TWIST, IN-FIGURE BEND

Figure 2. Alignment rod.

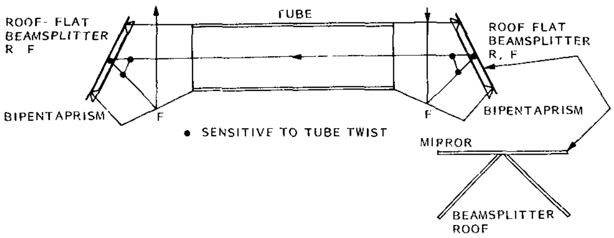
beam out of the plane of the figure. If the roof pentaprism and ordinary pentaprism were interchanged, the same tube bend would produce an angular shift in the opposite direction. This observation implies that if the roof and ordinary pentaprisms could be combined, the two retroreflectors formed by the combination would angularly shift their output beams in opposite directions in response to a given tube bend. The average of the angular centroids of the two beams would be independent of tube bend. This is the principle of the Alignment Reference Transfer System (called ARTS) to be described.

The ARTS is a pentaprism retroreflector in which the pentaprisms on both ends of the tube are a combination roof and ordinary pentaprism called a bipentaprism. The combination is accomplished by a beamsplitter. One of the possible configurations of the ARTS is shown in Figure 4. Because of the double beamsplitting, four output beams are generated from a single input beam. Two of these beams are retroreflected having passed through a roof pentaprism and an ordinary pentaprism in opposite order. The average angular centroid of these two beams is independent of tube bend. The other two beams having passed twice through the same type of pentaprism are reflected rather than retroreflected in one axis. Although these beams may be used for alignment of the ARTS, they are generally ignored or blocked. The ARTS described above is still sensitive to tube twist in first order. Sensitivity to twist is, however, much less damaging than sensitivity to bend, since the tube resistance to torsional deformation is higher than its resistance to bend, and since thermal gradients tend to produce bends rather than twist. Still, a twist monitoring sensor capable of subarc second accuracies would be a welcome addition to the ARTS concept.



- SENSITIVE TO TUBE TWIST OUT OF FIGURE BEND
- SIMPLE CONCEPT IF TUBE BEND IS CONTROLLED

Figure 3. Pentaprism retro.



- SENSITIVE TO TUBE TWIST

Figure 4. Bipentaprism retro (ARTS).

ARTS design trades

Several ARTS configurations are possible; the selection between them may depend as much on physical constraints in the systems to be aligned as on the reasons used in the following paragraphs. The selected baseline is shown in Figure 5.

(1) The alignment beam may fill the roof pentaprism or be limited in extent to only one side of the roof. In the baseline, the latter option was selected to avoid problems of discontinuity of wavefront tilt and light scatter from mirror surface joints. This option will produce two separated beams which travel along the ARTS tube.

(2) The beamsplitting element may be either the flat or the roof. In the baseline shown in Figure 5, the roof element was selected as the beamsplitter. This configuration is selected since the two beams which pass through the ARTS tube are separated in the plane perpendicular to the input beams. This particular configuration is better suited to our system constraints. Figure 6 shows a configuration in which the flat is the beamsplitting element.

(3) The alignment beam may make a single or double pass through the beamsplitter. The double pass configuration was selected to avoid the requirement of placing the flat behind the roof by a sufficient distance to allow separation of the incident and reflected beams

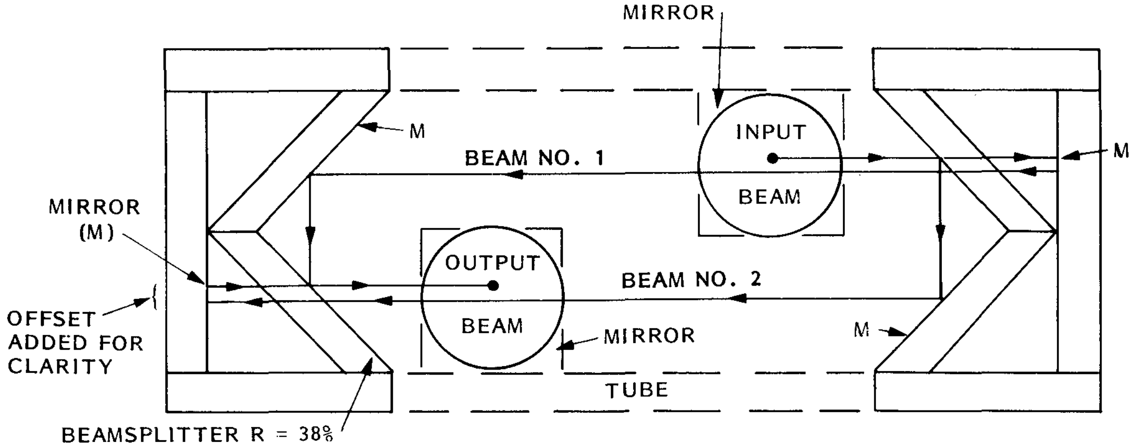


Figure 5. Baseline ARTS configuration.

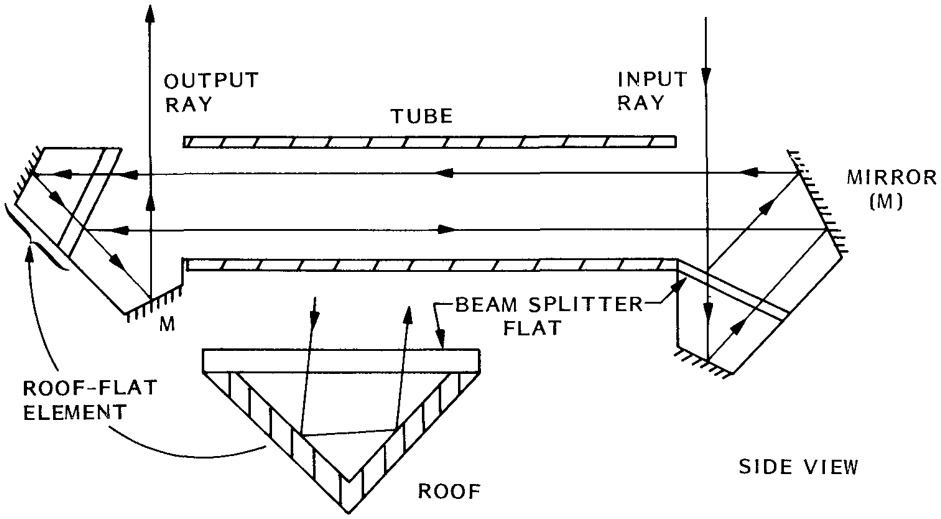


Figure 6. Alternate ARTS configuration.

on the beamsplitter. In the double pass configuration, each of the two ARTS output beams is 0.14 of the input beam intensity.

(4) It is possible to eliminate the beamsplitter completely and construct the lateral transfer system out of two pentaprism retros. This option has no common elements and is more sensitive to relative angular drift between mirrors. It does eliminate problems of thermal gradients through the beamsplitters.

Beam path through the baseline ARTS configuration

The path of an input alignment beam through the baseline ARTS configuration shown in Figure 5 is as follows:

(1) An input beam into the figure is reflected off the input mirror at an incident angle of 22.5 degrees and, rising (out of the figure) at an angle of 45 degrees, is directed to the first beamsplitter on the right.

(2a) A portion of this beam is transmitted through the first beamsplitter to a mirror. This mirror forms a dihedral angle of 45 degrees with respect to the input mirror. The beam, designated as number 1 in the figure, is reflected from this mirror and passes through the beamsplitter and ARTS tube in the plane of the figure. It is the beam traversing the penta to roof-penta path.

(3a) Beam number 1 is reflected off a roof formed by a mirror (M) and the second beamsplitter. After the roof, beam number 1 travels down and to the right at 45 degrees.

(4a) On reflection from the output beam mirror, beam number 1 is nominally antiparallel to the input beam.

(2b) A portion of the beam from the input mirror is reflected by the first beamsplitter. After reflection by the second mirror of this roof, this beam, number 2, travels through the tube in the plane of the figure. It is the beam traversing the roof-penta to penta path.

(3b) Beam number 2 is transmitted through the second beamsplitter to a mirror forming a dihedral angle of 45 degrees with the output mirror. After passing back through the second beamsplitter, beam number 2 is coincident with beam number 1.

(4b) On reflection from the output mirror, beam number 2 is nominally antiparallel to the input beam.

The baseline configuration shown in Figure 5 has identical input and output assemblies. This feature should simplify fabrication in that only one set of assembly fixtures need be made. The ARTS consists of input and output heads and a tube connecting them. The baseline configuration has only two output beams since the output mirror does not extend across the tube diameter. A working model of the ARTS was built and is shown in Figure 7.

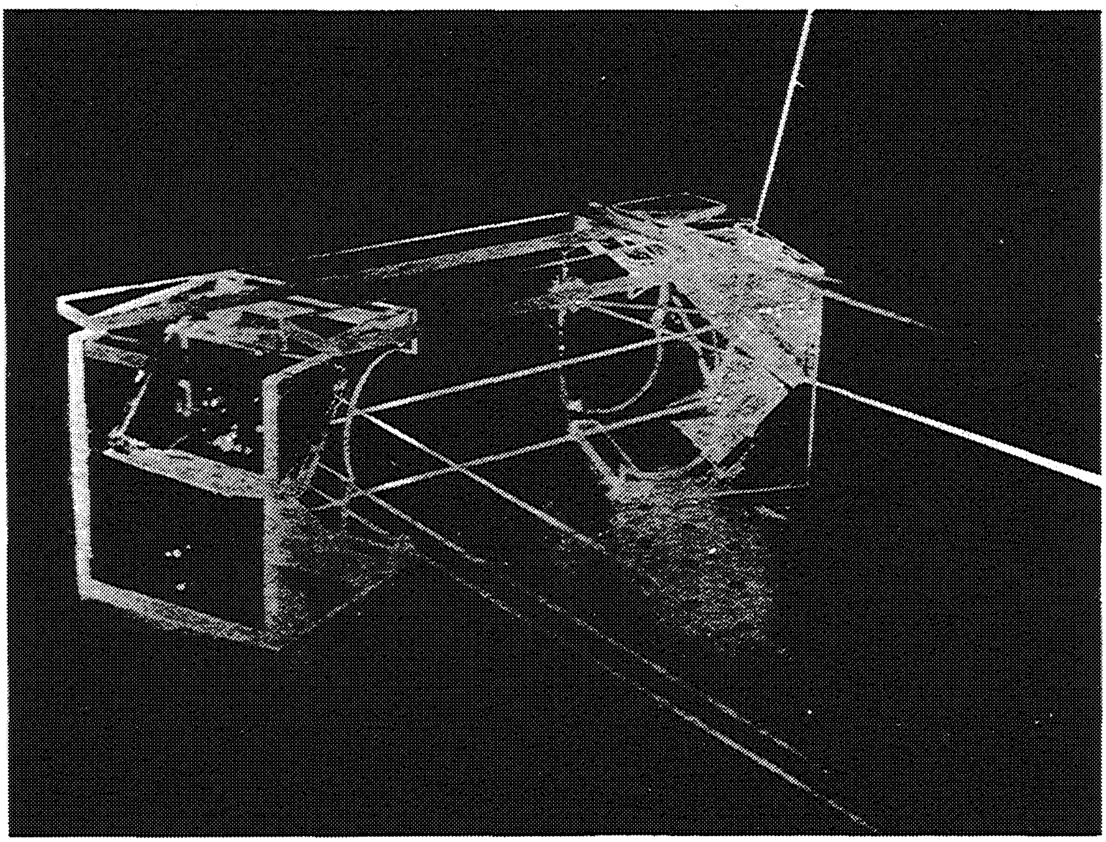


Figure 7. Photograph of the ARTS plexiglass model.

Current state of the ARTS error model

The two ACCOS-V types of pentaprism retros (roof-penta to penta and penta to roof-penta) were modeled in ACOSS-V to determine the deviation of the output beam from the reverse of the input beam direction. Since in-plane bend (α), of the ARTS tube has no effect, errors considered were out-of-plane tube bend (β), and input beam misalignment to the ARTS in both the in-plane (αA) and out-of-plane directions (βA).

Figure 8 shows the results for an aligned ARTS. As the ARTS tube is bent the deviations of the output beams show the expected quadratic effect in α and linear effect in β. The two retroreflected output beams are deviated in opposite directions about the retroreflected input ray direction. Hence, the average angular centroid of two output rays is the retroreflected input ray direction.

Figure 9 shows the results for an ARTS misaligned by 0.1 degrees. The input beam to ARTS misalignment skews the parabolic trajectories of the output ray directions with tube bend so that the two output rays no longer move in equal and opposite directions about the input ray direction. With angles expressed in radians, the ARTS error αE and βE is the product of ARTS misalignment and tube bend with cross coupling; i.e., tube β bend and out-of-plane misalignment produce in-plane ARTS error, while tube β bend and in-plane misalignment produce out-of-plane ARTS error. A more detailed ARTS error model is currently being developed. Some of the other types of error coupling considered are:

1. Beam walk on slightly curved "flat" elements
2. Thermal gradients across the beamsplitters
3. Element position drifts
4. Construction errors and misalignment drifts
5. Construction errors and tube bend

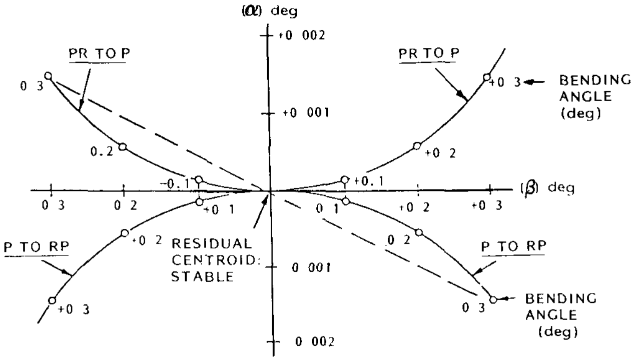


Figure 8. Retro beam error: aligned ARTS with tube bend.

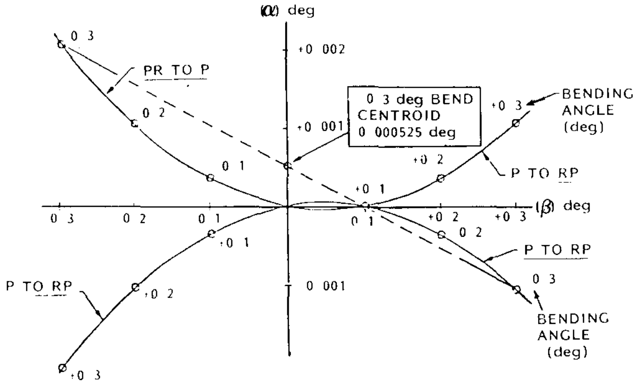


Figure 9. Retro beam error: misaligned ARTS with tube bend.

The lateral transfer system in perspective

Although the major thrust of this paper is to present a lateral transfer system concept, it is important to recognize that the lateral transfer of an alignment beam is only a part of the total alignment problem. The other elements of the problem include:

(a) System look angle references (typically flat mirrors - their surface normals represent the look angles to be aligned). These mirrors are called alignment reference mirrors.
(b) One or more alignment beam generators which provide collimated beams along the look angle references (typically a generator contains a point source, a lens, and an alignment reference mirror). Such a system is called an alignment assembly.
(c) The alignment beam transfer system (typically a retroreflector).
(d) Imaging systems and beamsplitters to convert alignment beam look angles to image positions (an autocollimator in some form).
(e) Detectors of image positions (a quadrant detector or array).

These elements of the alignment problem are shown schematically in Figure 10. Each of these elements has its own particular errors and applicable technologies.

The ARTS test configuration

The ARTS test is configured to eliminate as many as possible of the above errors by making them common path errors. The current approach for ARTS testing is to build two and test one against the other as shown in Figure 11. This test configuration eliminates, to first order, all errors in the alignment assembly which generates the collimated alignment beams and errors in the focussing optics which brings the collimated beams to focus for detection of the beam look angles. A common lens source, reference flat, imaging lens, and possibly even a common detector (if suitable chopping is implemented) ensures that the ARTS test responds only to drifts in the ARTS structure itself. The first ARTS would be the reference, while the second ARTS would be tested under thermal and structural stress characteristic of its expected environment.

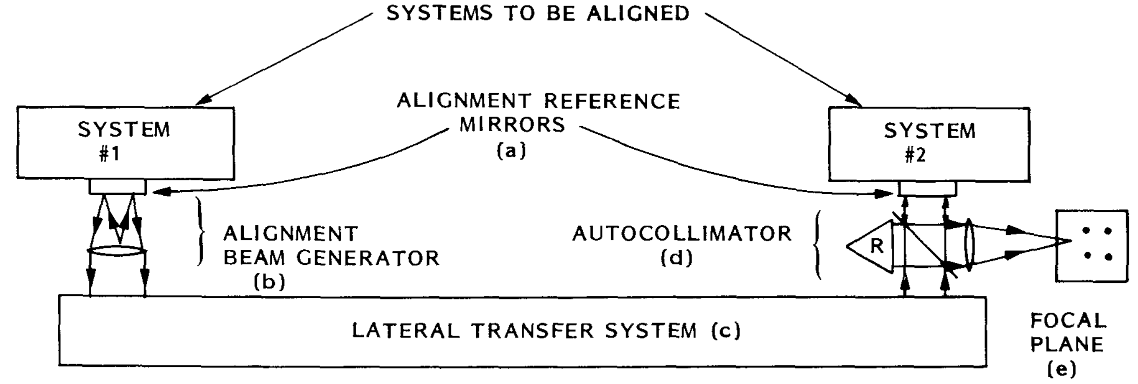


Figure 10. Components of alignment sensing.

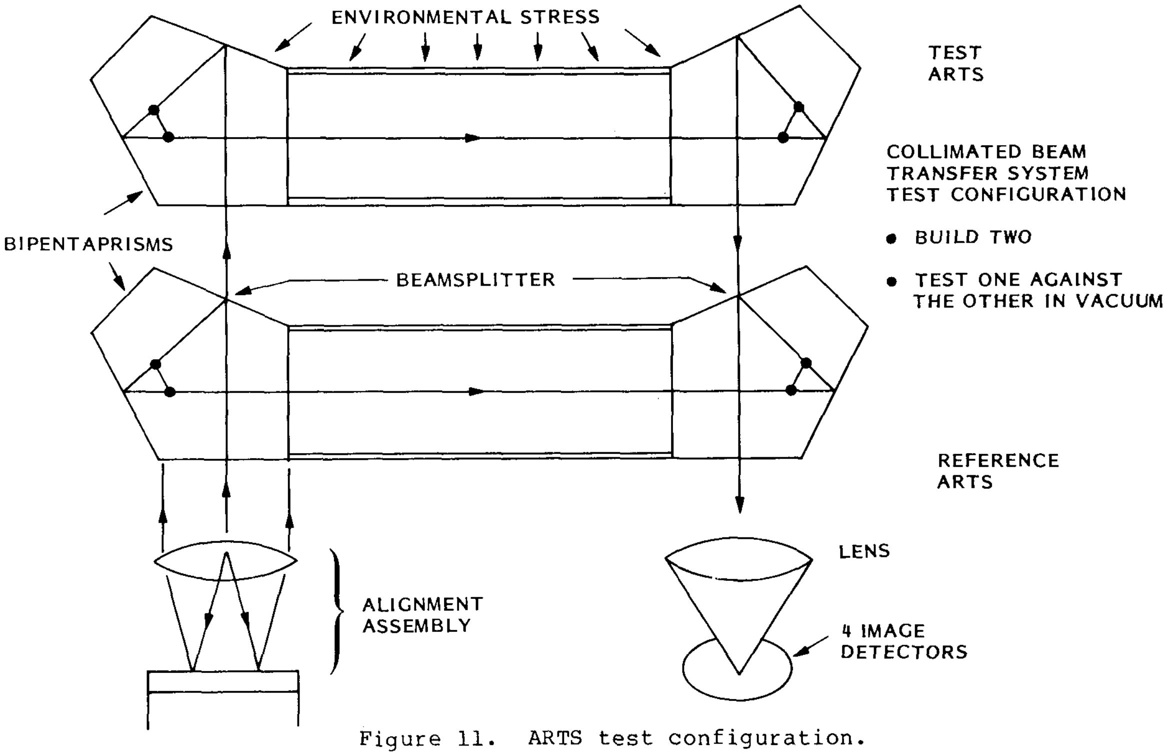


Figure 11. ARTS test configuration.

The use of the ARTS in a two-telescope boresight system

In the section to follow we assume that we must precisely sense the relative boresights of two telescopes having separate primary mirrors, imaging optics, and focal planes. (The word precision rather than accuracy is used to denote the fact that in space a reference wavefront from a star is available to establish a boresight calibration. The alignment systems are used to maintain the boresight established during the calibration in the absence of the reference wavefront. For this purpose, the alignment systems must be capable of a precise and repeatable measurement; small static angular offsets have minor significance.) The approach outlined represents an example of the use of the ARTS to obtain precision alignment of two independent optical systems. Other techniques would be more appropriate in many situations. First, we describe briefly the elements in the alignment problem listed above.

The alignment assembly

Figure 12 shows a configuration used to generate an alignment beam referenced to a look angle. The configuration consists of the alignment reference mirror, a lens separated from the mirror by one-half its focal length, and a point source at the lens nodal point. The

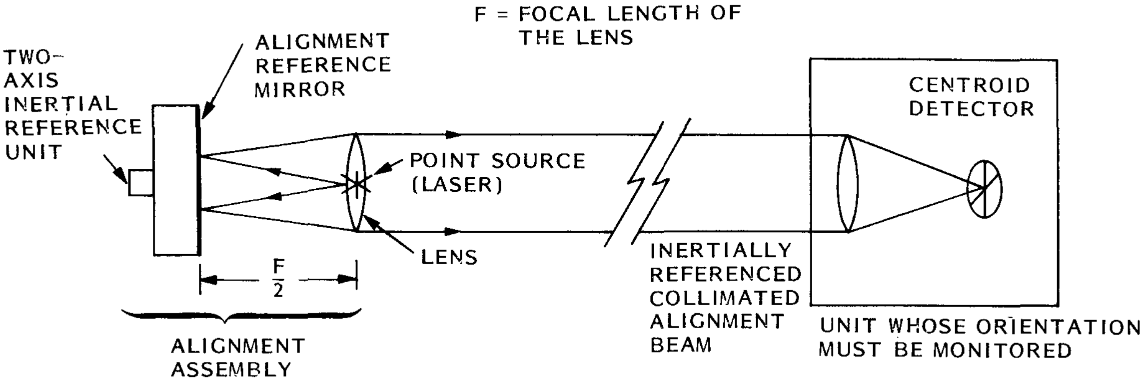


Figure 12. Alignment beam generation and use.

point source may be the output of a laser diode (0.83 μm) driven optical fiber rigidly attached to the lens. This configuration has the property that to first order the direction of the alignment beam is nominally along the alignment reference mirror surface normal independent of small misalignments of the lens. If required, this alignment reference mirror can be fitted with inertial sensors to provide an alignment beam which is inertially referenced.

Changing the lens to mirror separation will result in the generation of a focused rather than a collimated alignment beam. In the focused beam case, the location of beam focus will depend only on the orientation of the reference mirror and the lateral position of the lens and will be independent, to first order, of the lateral position of the mirror and the orientation of the lens. This physical separation of position and angular sensitivity onto two separate components is often useful.

The autocollimator optics

The function of the autocollimator is to measure the look angle of the alignment beam from the ARTS relative to the local alignment reference mirror. Figure 10 shows a possible optical configuration. The twin alignment beams output from the ARTS enter a beamsplitter. Part of both beams are reflected off of the alignment reference mirror, while part of both beams are retroreflected by the cube corner. After beam recombination by the beamsplitter, the angular difference between the two sets of alignment beams is the angular difference between the input alignment beams and the mirror normal. The configuration is independent of small changes in the orientation of the beamsplitter relative to the mirror. A lens at the output of the beamsplitter images the four alignment spots onto a detector for image centroiding. The four images are separated on the detector to avoid centroid pulling by intensity variations.

The autocollimator detector

The function of the detector is to measure the centroids of the focused alignment beam images. This measurement must be to high angular precisions because of the relatively small diameter of the alignment beams. For example, if the alignment beam diameter is one percent of the telescope diameter and a telescope boresight error of ten percent of the Airy disk diameter is allowable, centroiding of the Airy disk to better than 0.1 percent is required. Such precisions have been demonstrated on random access CID arrays and on quadrant detectors in the visible.

Conclusions

The ARTS is an extended retroreflector configuration which uses beamsplitters in the retro to generate two retroreflected output alignment beams. The average angular centroid of these two beams is insensitive in first order to bend in the tube connecting the input and output assemblies. Compensation for the effects of tube bend allows a reduction in the volume through which thermal and structural stress must be tightly controlled. Only the input and output assemblies must be highly protected from the environment.

Acknowledgments

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