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Integrated Radio and Optical Communications (iROC) Primary, Secondary, and Tertiary Optics Alignment Procedure

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July 2020

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subject to revision as analysis proceeds.

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Summary

This Technical Memorandum (TM) describes a procedure and associated equipment for performing an initial, relative alignment of a multiple-element optical system. The specific system of interest motivating this procedure arises from the Integrated Radio and Optical Communications (iROC) project, but is applicable to the more general configuration of a two-element folded, reflective telescope. Each step of the procedure includes a description of the particular degree of freedom (DOF) being addressed, and the associated equipment required, including both commercially available items and those fabricated specifically for this purpose. In the case of the former, the key performance factors are listed to allow substitution of equal capabilities as available. For the latter, sufficient specifications are provided to facilitate their construction. The resulting accuracies achievable for the alignment of each applicable DOF are noted and compared with the absolute accuracies required for this specific application of interest.

1.0 Introduction

The alignment procedure described here is motivated by the requirement to align the optical system for the Integrated Radio and Optical Communications (iROC) terminal. The architecture of this terminal is designed to support hybrid (simultaneous) radiofrequency (RF) (32 GHz) and optical (1,550 nm) space communications. By incorporating both radio and optical modes of communications into a single terminal, a high level of communications system robustness is achieved while providing reductions in size, weight, and power over segregated radio-only and optical-only terminals.

The iROC terminal includes a special telescope and antenna system—or ‘teletenna’ in which both radio and optical waves are effectively focused and transmitted toward earth receivers. The eventual construction of the flight version of the teletenna will require consideration of both mechanical and thermal features of all aspects of the individual elements and supporting structure to assure that required alignment is maintained in the actual operational environment. Collocating the optical and RF features together in a single structure requires numerous enabling technological developments, including RF-translucent materials for the teletenna structure, and a suitable dichroic element to combine and launch the respective optical and RF sources.

The intent of the project is to provide communications links suitable for deployment beyond lunar distances. Operation at these distances fundamentally excludes the use of a conventional uplink beacon to aim or point the transmitter with sufficient accuracy towards receivers located on Earth or other orbiting platforms. The iROC system achieves stabilization and pointing of the optical beam through the use of a single star tracker to establish absolute attitude sensing.

This report describes a procedure and associated equipment for aligning the optical portion of the combine teletenna. The present design is of the Cassegrain type, a folded design comprised of a parabolic primary mirror and a hyperbolic secondary mirror. This set of procedures also addresses the alignment of additional optics called the tertiary assembly, which is used to couple the optical laser source into the

Cassegrain telescope itself. This set of procedures and apparatus is applicable to the more general class of two-element folded, reflective telescopes. The prescription for the specific assembly of interest here is provided in the associated document "Baseline Optical Design of Integrated Radio and Optical Communication System" (Ref. 1, to be published).

Initial alignment speaks to the resulting accuracy relative to that required to achieve the overall targeted system performance. The required performance criteria can be found in the aforementioned design document, along with the calculated positioning tolerances for each individual element. It is noted that the latter presently represents only the diagonal (decoupled) tolerances, that is, each tolerance being calculated assumes all other elements of the system are in perfect alignment. The accuracy obtained by the initial alignment method will be compared to these calculated tolerances. The intent of this procedure is to establish sufficient alignment to allow further interrogation and fine adjustment using more precise techniques, such as interferometry or wavefront analysis.

Setting aside details such as diffraction from mechanical support structures, imperfections in the optical elements themselves, and possible thermal and mechanically induced distortions, the objective is to produce an emitted beam that is diffraction limited. This is complicated in practice by the need to truncate the Gaussian beam profile at some specified diameter. For the present system, the full aperture is chosen to correspond to the $1/e^2$ intensity points of the emitted beam.

The basic configuration and degrees of freedom (DOFs) are shown in Figure 1. The quantities Δx, Δy, and Δz correspond to lateral distances, and $\Delta\theta_x$ and $\Delta\theta_y$ corresponds to the angular tilts along the x and y coordinates as specified in radians.

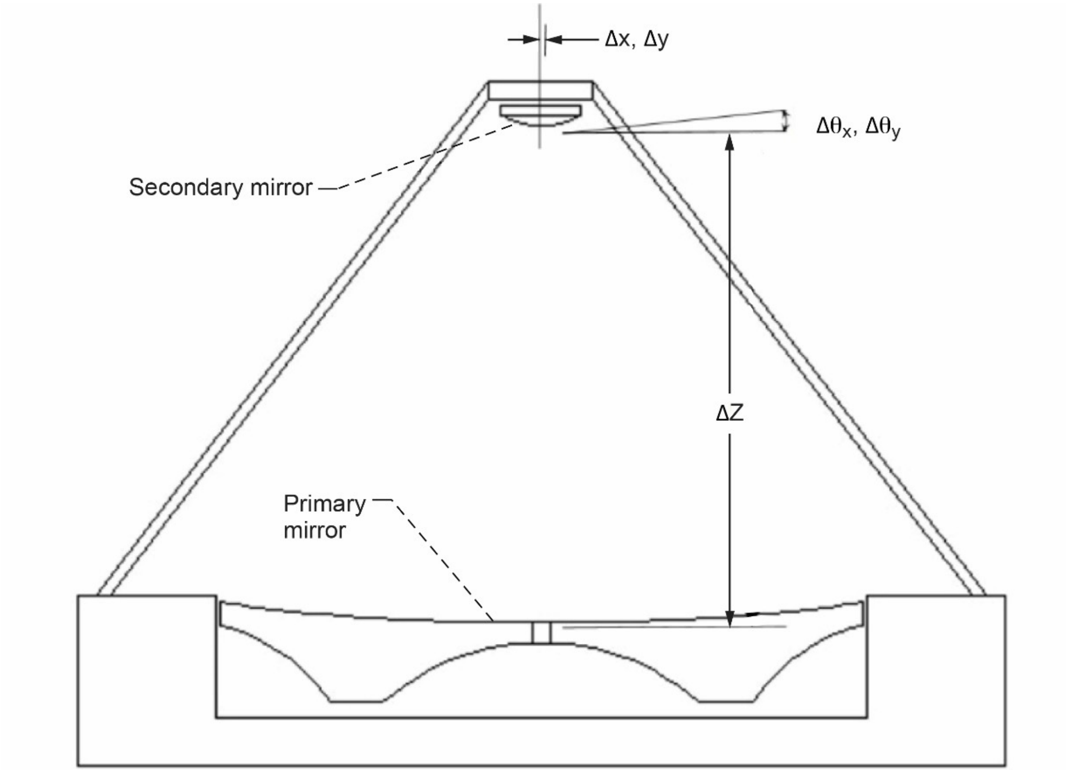

Figure 1.—Integrated Radio and Optical Communications (iROC) mirrors and degrees of freedom.

TABLE I.—PRIMARY AND SECONDARY MIRROR RELATIVE ALIGNMENT TOLERANCES

Degrees of freedom (DOFs)	Model tolerance	Alignment precision
Tilt $\Delta\theta_X$, $\Delta\theta_Y$[a]	2.86×10^{-4} degrees 4.99 μrad	5 μrad
Centration ΔX, ΔY[a]	0.548 μm	5 μm
Axial spacing ΔZ[b]	46.7 μm	10 μm

[a] For maximum chief ray deviation of 1 μrad.

[b] For maximum wavefront deviation of $\lambda/4$ at 1,550 nm.

The alignment tolerances derived from the design model and the associated accuracies obtainable from this alignment procedure are listed in Table I.

The procedure described herein is intended for initial system alignment, and as such is only required to achieve a resulting accuracy lying within an order of magnitude of the final required precision. As seen in Table I, the model tolerance predictions for tilt and axial spacing are accommodated or exceeded, whereas the required centration accuracy fall short by roughly an order of magnitude.

2.0 Apparatus

This section contains a list of items necessary to perform the procedures for aligning the primary and secondary mirrors. For those commercially available items, a description is provided to allow the substitution of functional equivalents from other sources. Relevant specifications are provided for items that have been custom fabricated to afford their construction. Note that a separate Section 4.0 follows pertaining to the associated tertiary optics.

A. Commercial components:

1. Optical autocollimator, Newport Corporation CONEX–LDS, minimum required angular resolution (rad) needs to equal or exceed the permissible relative tilt of primary and secondary mirrors. The autocollimator must be located on a suitably precise and stable 5-axis translation mount. The measured accuracy for the CONEX–LDS used here is approximately 0.5 μrad after a suitable warmup period.
2. Optical position sensitive detector (PSD), On-Trak Photonics, Inc., PSM2–4, minimum required lateral detection sensitivity needs to equal or exceed the permissive relative primary and secondary decentration. The threshold luminous sensitivity must be sufficient to resolve a suitably apertured beam from the autocollimator. The stated accuracy for the PSM2–4 used here is 200 nm.
3. Optical rail and cart assembly, minimum travel corresponding to primary and secondary axial spacing.
4. Two focusing lenses, where the difference in focal lengths is approximately equal to the primary and secondary axial separation. The shorter focal length lens must reside in a mount that can be attached to the exit of the autocollimator. The longer focal length lens is mounted in an x, y translation mount that can be attached to the autocollimator. Lenses of focal lengths 40 and 500 mm, respectively, were used here.

B. Noncommercial components:

1. Two reflective targets, as shown in Figure 2, both must fit into the same mount as the secondary mirror.
2. One target is a reflective optical flat. The second is a reflective convex surface, whose radius of curvature is on the order of one-tenth or less of the shorter focal length lens described in list A.2. In this example, both targets were single-point diamond turned from 6061T-6 aluminum. The stem tap is not a critical feature and is only provided as a convenience to ensure the anchoring of the targets in their respective mounts.
3. The ability to mount these two targets concentrically in the primary mirror requires an adapter or collar. The tolerance on the concentricity of this collar and the through hole in the primary mirror must equal or exceed the allowable primary and secondary lateral tolerance. Because this collar will also be used in Section 3.4, the location of the face of this collar relative the vertex of the primary mirror must be known to a tolerance equal to or exceeding that of the primary and secondary allowable axial tolerance.
4. A metering rod and two metallic button contacts to set the primary and secondary axial spacing. Ideally, the rod itself should be made from a low coefficient of thermal expansion material (i.e., ceramic or graphite). It can be machined to length directly or made as an adjustable assembly. The minimum tolerance of the length must equal or exceed the specified tolerance for the primary and secondary axial spacing, while the button contacts must fit in the same mount and adapter as described in list A.1. The thicknesses of both buttons (from the back to front faces) and the dimensions of the primary mounting collar must be known to a minimum tolerance of the required primary and secondary axial positioning requirement. In this example, this tolerance was achieved by single-point diamond turning of the buttons.

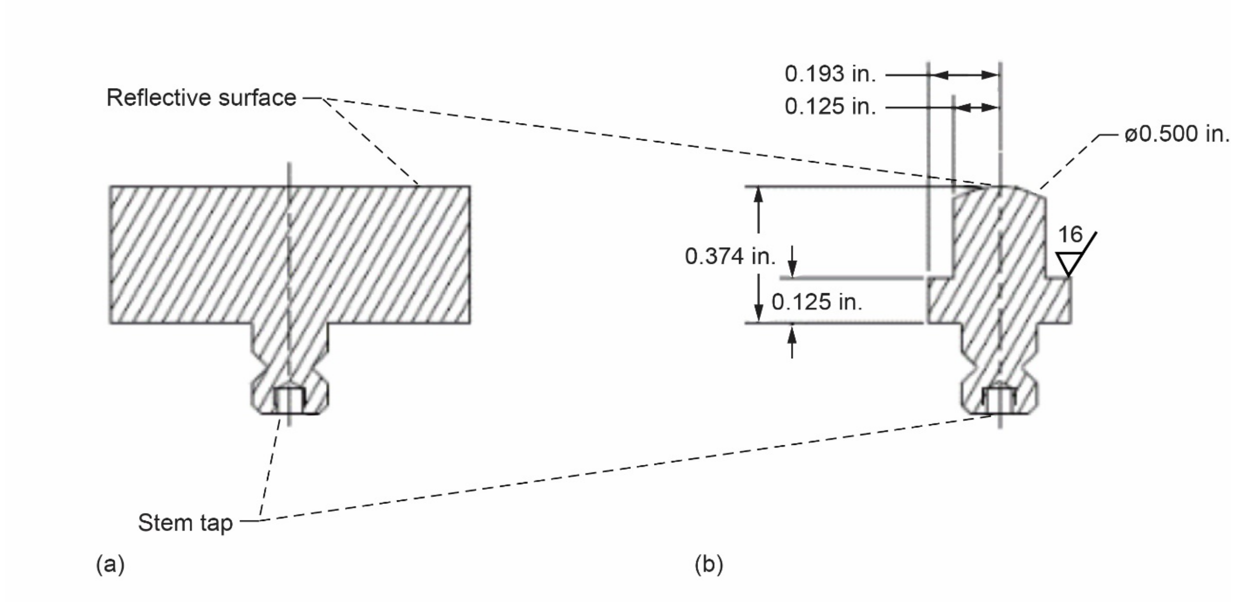

Figure 2.—Reflective targets. (a) Flat. (b) Convex.

3.0 Overview of Process: Alignment of Primary and Secondary Mirrors

The objective of this process is to align the 5 DOFs in the relative positions of the primary and secondary mirrors: two tilts and two lateral centrations of each and their axial spacing. Section 4.0 describes procedures for aligning the tertiary optics.

Alignment of the primary and secondary optics is accomplished in three steps. In this system, the optical axis and plane of the primary mirror serve as the reference, due to mass of this element and relative difficulty in providing a five-axis mount for adjusting its position.

The first step involves using an autocollimator to remove the four tilts. The second step utilizes focusing lenses in combination with the autocollimator to align the centrations. In the third and final step, a metering rod is used as a reference to set the axial spacing.

3.1 Use of Optical Rail To Align Focusing Lenses

Using a pair of focusing lenses to gauge centration is only effective if the focal points of these respective lenses are themselves accurately centered. Achieving the required accuracy from two separate lenses in fixed mounts is impractical to achieve in practice. Described here is a procedure for establishing the alignment of these two foci.

The lateral position of the respective focal points is determined with a suitable PSD that is translated the length of the rail. These measurements need only be performed at the two distances corresponding to the foci of the lenses, so the straightness of the rail itself is not a consideration. However, the quality in terms of repeatability of the cart is important. This process is shown schematically in Figure 3.

The lateral centrations of the foci need to only be established in the relative sense. As such, one lens can be placed in a fixed mount and the other in a laterally adjustable mount. While not strictly required, fixing the shorter focal length and adjusting the longer is easier in practice. The longer throw affords the use of a stage with a relatively small range of travel, and the smaller corresponding displacements of the lens result in less aberration of the focused image.

The autocollimator is visually positioned to be roughly coincident with the axis of the rail. The PSD is then translated along the rail to determine the axial locations of the two focused spots, and these locations marked on the rail or set through the use of stops. The lateral position of the collimator output beam is then measured for one axial location of the PSD. The exit beam of the autocollimator may need to be reduced by an iris or other aperture to comply with the spatial dimensions of the PSD. The PSD is then walked between the two axial locations and the angular orientation of autocollimator iteratively adjusted until the PSD registers the same lateral location at both distances. Achieving this ensures the centroid of the autocollimator beam is coincident with the rail at these two axial locations.

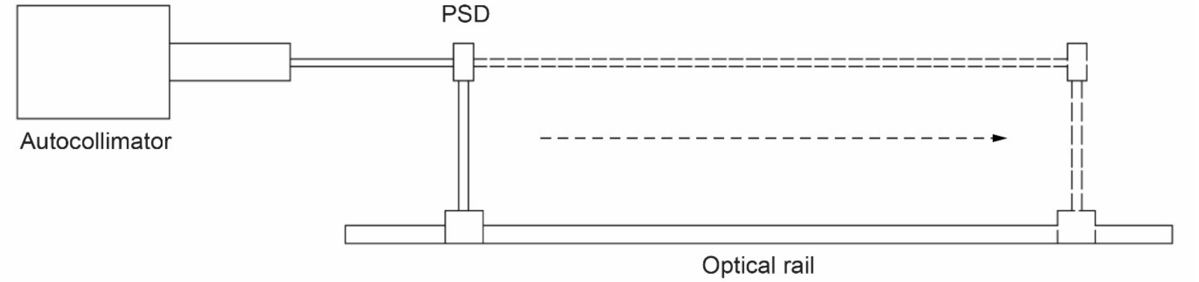

Figure 3.—Use of optical rail to coalign autocollimator and position sensitive detector (PSD).

The first, shorter focal length lens is mounted to the autocollimator and the lateral positon of its focal spot on the PSD recorded. The PSD is then shifted to the larger focal position, and the second lens in its adjustable mount fitted to the autocollimator. The lateral position of this mount is then adjusted to bring the second focus into coincidence with the previously recorded location of the first. When this is completed, the mount should be locked or potted in place.

3.2 Removal of Tilt

This step involves using the autocollimator and the flat reflective target to remove the four tilts. It is again noted that the optical axis of the primary mirror serves as the reference optical axis for the system. In this step of the procedure, the angular alignment of the autocollimator is established relative to this reference axis, and this alignment must be preserved in the subsequent procedure for establishing centration (i.e., once the autocollimator's location is fixed, it cannot be moved or its angular adjustment disturbed). To achieve this, prior to executing Sections 3.2 and 3.3 of the procedure, the shorter focusing lens should be mounted to the autocollimator, the convex reflective target installed in the primary mirror, and the axial position of the autocollimator mount adjusted such that the focal point coincides with the optical surface of this target. The resulting geometry is best appreciated from Figure 6(a). The actual alignment of centration is not performed until Section 3.3, but this provision must be first addressed here to ensure the autocollimator has been placed properly for the reasons described.

This setup is shown schematically in Figure 4. The target is initially located in the primary mirror, and the autocollimator adjusted to be normal to this surface. The target is then moved to the location of the secondary mirror, and the secondary mount adjusted to align it normal to the autocollimator, bringing this element into planar alignment with the primary mirror.

3.3 Establishing Centration

Figure 5 illustrates the geometric relationship between the autocollimator, focusing lens, and target forming the basis for the measurement of centration. Because of the curvature of the target, small decentrations δ cause the incident beam to impinge at a slight deviation of the surface normal $\vec{n}$. The resulting reflected cone of illumination is angularly displaced, and this angular deviation measured by the autocollimator. Here, f is the focal length of the focusing lens and r is the radius of curvature of the target.

In Figure 6, the convex target is first located concentrically in the primary mirror. The shorter length focusing lens is mounted on the exit of the autocollimator, and the autocollimator adjusted laterally in two axes to bring it into alignment with the optical axis of the primary mirror. The target is then moved to the location of the secondary mirror, and its mount used to remove the decentration of this element relative to the previously established reference axis of the primary mirror.

3.4 Axial Alignment

This final step establishes the primary and secondary axial separation. One contact button is installed in the primary collar or adapter as described in Section 2.0 list B.4. The second button is installed in the secondary mount. It is assumed that the length of the metering rod has been previously established, either through fabrication or adjustment. The axial position of the secondary mount is then slowly advanced until physical contact between the rod ends and the button faces occurs.

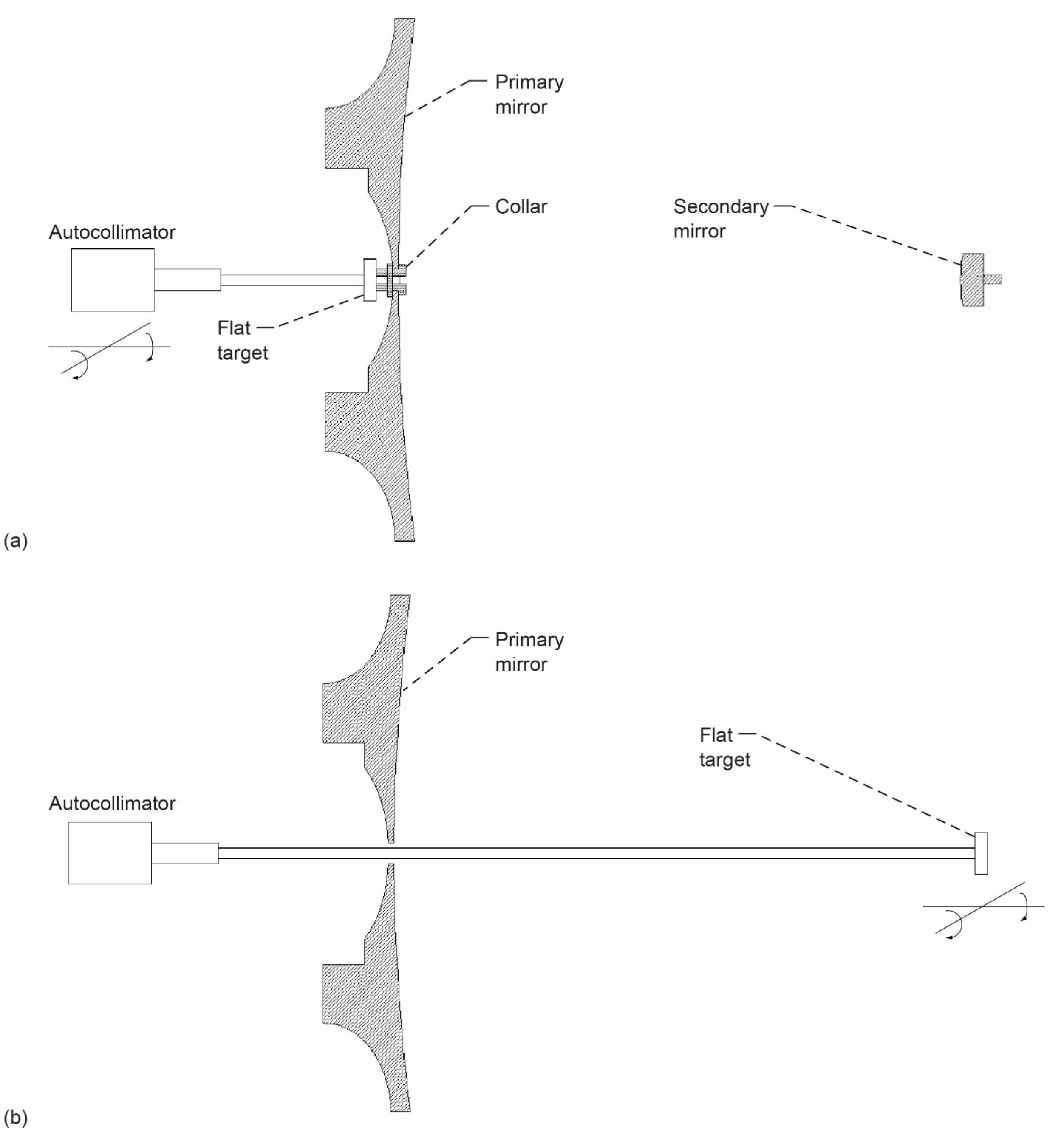

Figure 4.—Autocollimator and flat target. (a) Coalignment of autocollimator and primary optical axes. (b) Removal of secondary relative tilt.

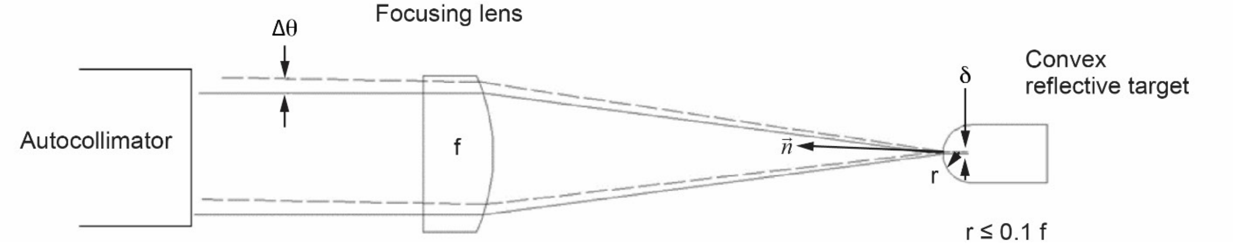

Figure 5.—Measured angular shift (θ) caused by decentration (δ). Surface normal ($\vec{n}$). Focal length of focusing lens (f). Radius of target curvature (r).

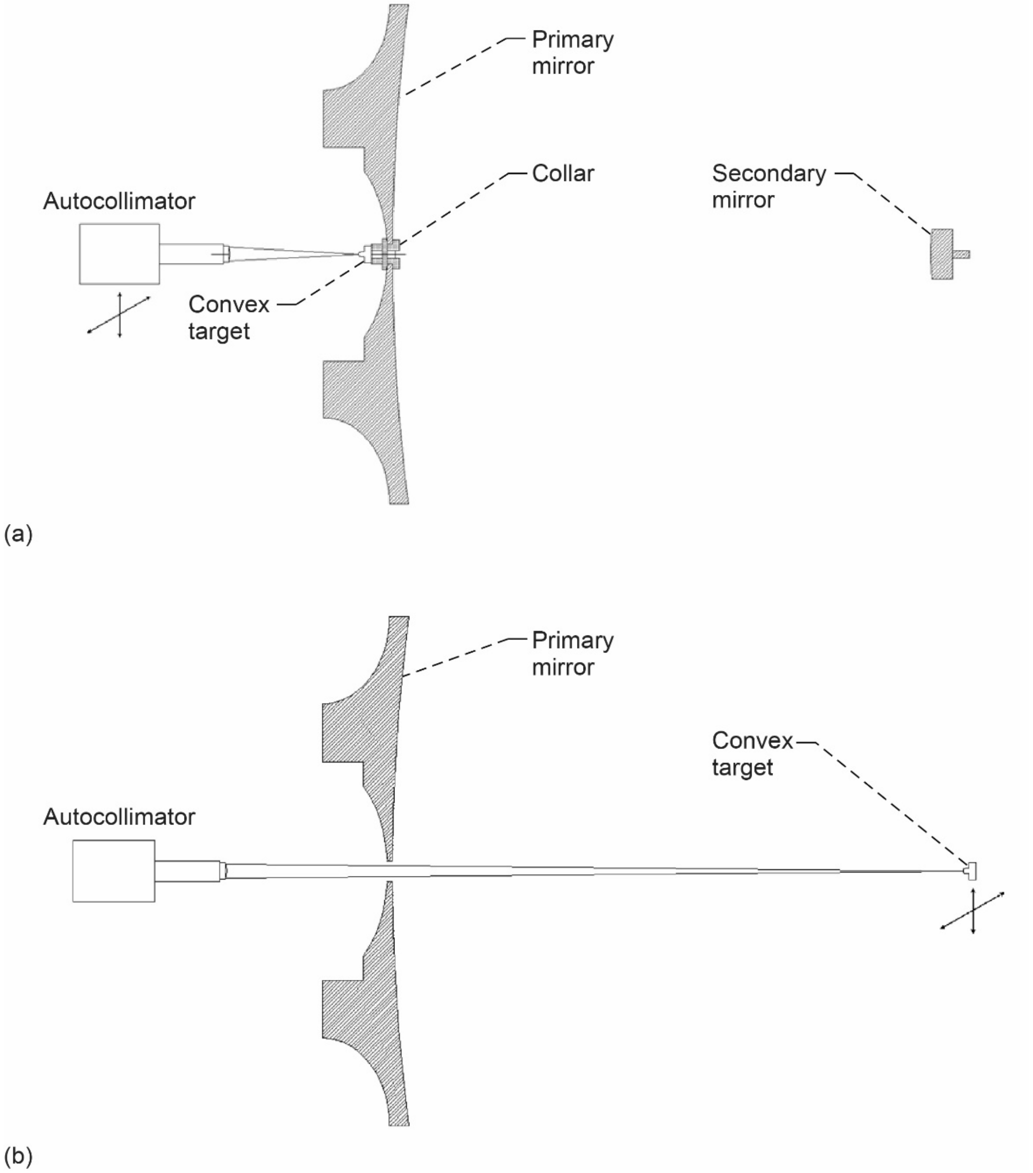

Figure 6.—Autocollimator centration. (a) Coalignment and primary centration. (b) Relative centration of secondary optics.

4.0 Tertiary Optics Tube Alignment

The laser source is coupled to the telescope optics (primary and secondary mirrors) by an assembly called the tertiary optics tube. A diagram of this assembly is shown in Figure 7. In sequential order, the laser source is introduced via a single-mode optical fiber. The fiber output is collimated by a short focal length aspheric lens. The present version uses a commercially available lens and mount (FiberPort by Thorlabs, Inc.), which also provides the 5 DOFs for alignment. The collimated beam then passes through a polarizing beam splitter (PBS) cube and quarter-wave ($\lambda/4$) phase retardation plate, the function of which will be described later. The polarization sensitive nature of these two elements requires the input fiber to be polarization maintaining. The collimated beam is then mode matched to the telescope optics in a Galilean configuration, utilizing a convex coupling lens to match the numerical aperture of the diverging beam to that of the telescope itself. The θ_{NA} is the divergence angle exiting the coupling lens and the matching entrance cone of the telescope optics.

The PBS and $\lambda/4$ phase retarder plate are used to implement various beam diagnostics in a double-pass configuration. If the beam exiting the telescope is reflected back into the system (i.e., double-passed), the resulting polarization is rotated by 90° by virtue of having traversed the retarder plate twice in total. The PBS then redirects this beam horizontally, where it can be assessed in various ways. One motivation to use this configuration is to assess the return beam to characterize the pointing accuracy of the telescope when subject to different mechanical misalignments or perturbations.

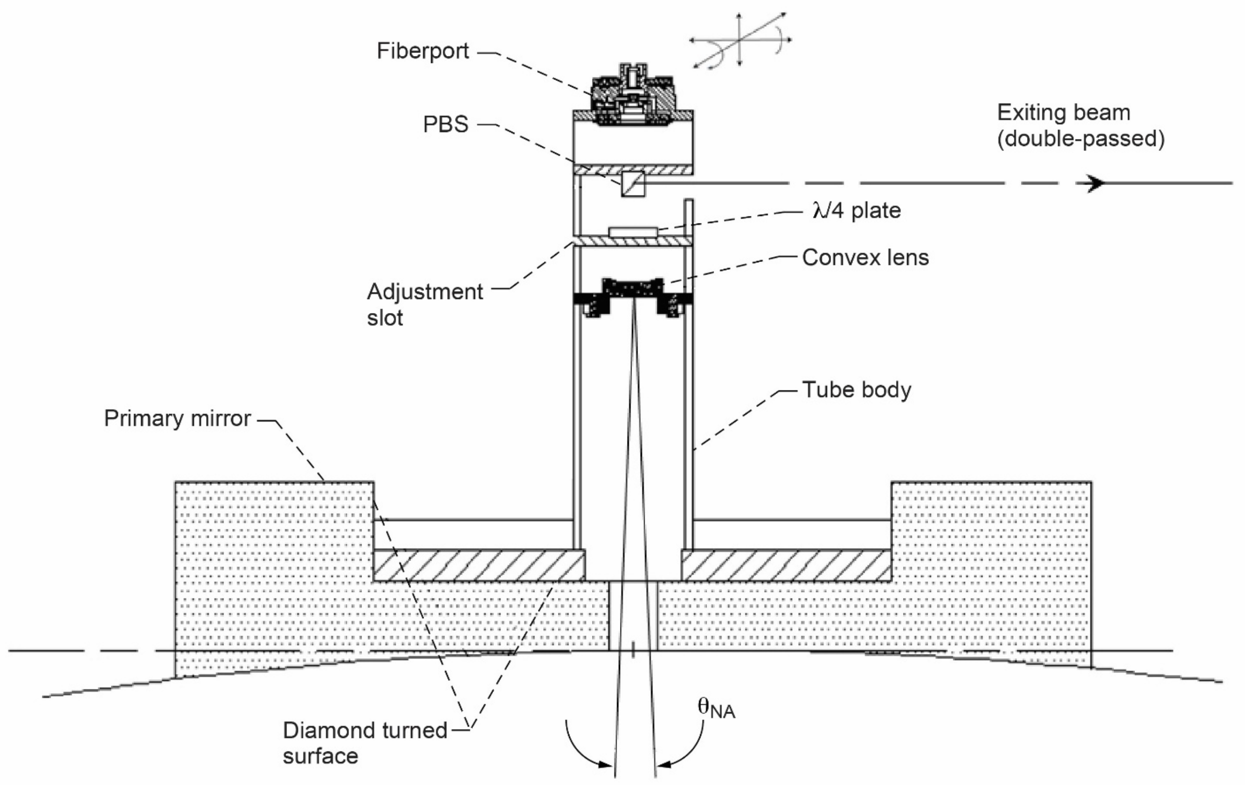

Figure 7.—Tertiary tube assembly. Quarter wave ($\lambda/4$). Polarizing beam splitter (PBS). Divergence angle exiting the coupling lens and matching entrance cone (θ_{NA}).

The sides and foot of the tube body are single-point diamond turned, and the associated mating surfaces in the primary mirror are similarly finished. For the latter, this operation is performed in conjunction with the machining of the mirror surface, ensuring that these features are precisely coaligned. The foot and bore of the tube are machined in an analogous fashion, ensuring similar precision. The process of tertiary alignment is then reduced to aligning the beam to be centered and parallel to the axis of the tube itself. Since slight wedges or tilts in either the PBS or retarder plate will result in associated offsets of the beam passing through these elements, the tertiary alignment is done with these elements already in place.

It is noted that the tolerances in Table I express the positions of the primary and secondary mirrors relative to each other. The approach here establishes the axis of the primary mirror as the reference coordinate system, and was adopted for practical reasons. Since the primary mirror is the largest and most massive element, from a design perspective it is simpler to fix it in place and adjust the relative alignment of the remaining elements. As indicated, the present design also mounts the tertiary tube directly to the primary mirror, with registration achieved by precise diamond turned surfaces machined into the mirror simultaneous with the machining of the optical surface itself. The specified accuracy of this operation is approximately half a wavelength in the visible range, and can therefore be neglected relative to other alignment uncertainties. For these reasons, the tolerances listed in Table I effectively provide the alignment tolerances for the concentricity and tilt of the optical beam relative to the tertiary tube.

4.1 Equipment

The following is a list of required items for the alignment of the tertiary tube assembly. For those commercially available, a description is provided to allow the substitution of functional equivalents from other sources. Relevant specifications are provided for items that have been custom fabricated.

A. Commercial components:
   1. Optical power meter, Newport Corporation's 1830–C or equivalent. Detection resolution of 0.1 nW at the source wavelength.
   2. Beam profiler, Melles Griot BeamAlyzer (IDEX Health & Science, LLC) or Thorlabs, Inc., WM100 Omega Meter, or equivalent.
   3. Optical cage assembly, Thorlabs, Inc., CP0T2/ER24 or equivalent, 24 in. minimum length.

B. Noncommercial components:
   1. A 50- to 100-μm precision pinhole. While a pinhole of this type can be obtained commercially, the centration error is typically on the order of 3 times the nominal diameter. For this reason, this pinhole must be mounted independently using an alignment microscope, or machined directly into a precision concentric mount. A final centration of 2 μm or better is required to conform to the tolerances indicated in Table I.
   2. A concentric collar to adapt the cage rail to the tertiary tube. This collar is seen in Figure 9 and Figure 10.

4.2 Alignment of Polarization and Exit Beam

Before installing the individual elements into the tertiary tube, the polarization axes of the PBS and λ/4 plate must be coaligned. A schematic of this assembly is shown in Figure 8. Together with the spacer tube, these elements and their mounting plates are cemented as a single assembly. Alignment is established by passing a polarized laser beam through the combination, rotating the λ/4 plate, and using an optical power meter to maximize the output.

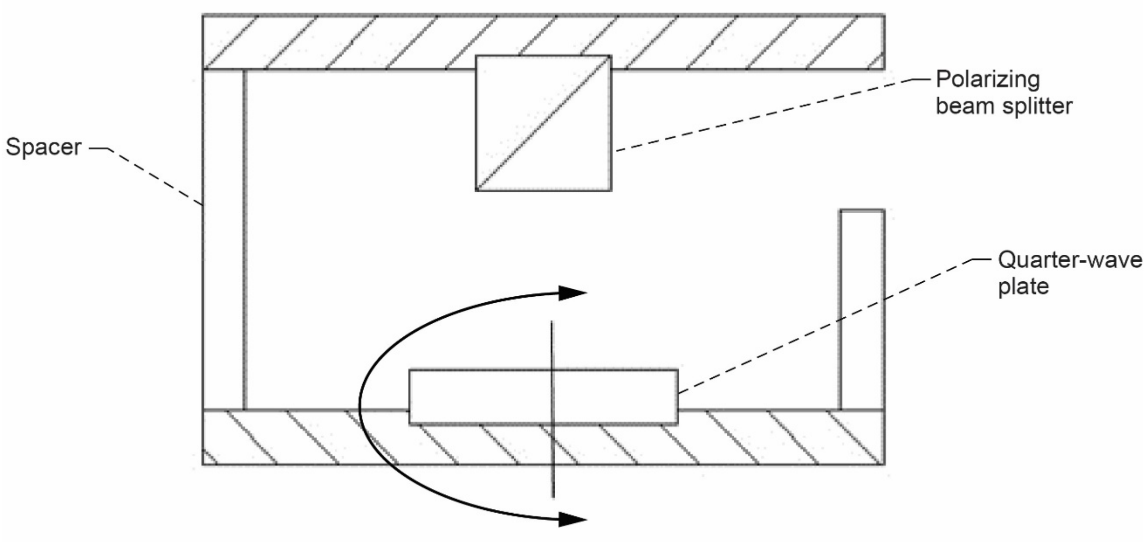

Figure 8.—Polarizing beam splitter and quarter-wave plate assembly.

Since the input fiber from the laser is polarized, its associated ferrule is keyed. The FiberPort assembly has a similarly matched key. As such, the FiberPort mounting holes on the upper surface and beam exit port of the tertiary tube must be correctly machined to ensure the proper polarization alignment of all these combined features.

The cemented assembly, convex lens mounting plate, and all additional spacers are then installed into the tertiary tube and locked into place using the threaded locking ring at the top of the tube. At this stage, the locking ring must not be fully tightened, but allow enough movement to rotate the cemented PBS assembly using the small alignment slot machined into the side of the tube. The FiberPort is affixed to the tube and connected to the source laser using the polarization maintaining optical fiber. The rotational position of the PBS assembly is then adjusted to appropriately point the exiting beam into whatever beam diagnostics are to follow using associated locating jigs or fixtures as necessary. The FiberPort is then temporarily removed to allow the locking ring to be fully tightened.

4.3 Beam Collimation

Before aligning the beam to the tertiary tube axis, the axial adjustment in the FiberPort assembly is used to collimate the emitted beam. This and the following procedure must be conducted with the convex mode-matching lens removed. The mount for this lens is fabricated as two nested, concentric pieces. These two pieces are diamond turned to ensure precise centration and parallelism. Similarly, the surfaces of the spacer following this assembly are also diamond turned to assure parallelism. The through hole at the foot of the tube assembly is sufficiently large to allow the removal of the inner portion of the mount and the lens for these procedures.

While both components of the mount are precisely machined, the lens itself must be registered relative to this assembly before being cemented in place. This is best achieved through the use of specialized equipment designed for this specific purpose. In lieu of this, an analogous process can be used. Before reinstalling the lens with the inner mount, an imaging array is placed at a location following position 2 in Figure 9. Digital capture and processing is used to determine the centroid of the collimated beam. The lens and inner mount are then placed in the collar and sequentially rotated and adjusted to remove any precession in the centroid of the resulting diverging beam. It is noted that although this centroid operation can be implemented with adequate precision, the required fixture and adjustment of the lens relative to the mount prior to cementing is not trivial.

The indicated beam profilers (or their equivalent) are used to measure the diameter of the emitted beam at several distances along the optical axis, iteratively adjusting the FiberPort until consistent diameter readings are obtained at all axial distances. In principal, measurements should be taken at the largest distance practically accommodated in the laboratory, or a similarly large distance replicated through the use of folding mirrors. Since the degree of collimation, or equivalently the wavefront quality, will subsequently be further adjusted to finer precision using a shear cube or wavefront sensor, an absolute accuracy specification for this procedure is not required.

4.4 Alignment of Beam Centration and Parallelism.

The tilt and centration adjustments of the FiberPort assembly are utilized to align the now approximately collimated beam relative to the tertiary tube. The adjustment screws used in a differential fashion for tilt also control collimation when used in parallel. For this reason, after completing this procedure, it is desirable to verify beam collimation as described previously and readjust if necessary.

Centration and parallelism are established using a rail tower as shown in Figure 9. When performing this operation, it is desirable to orient this tower vertically to avoid gravitationally induced sag in the rail structure.

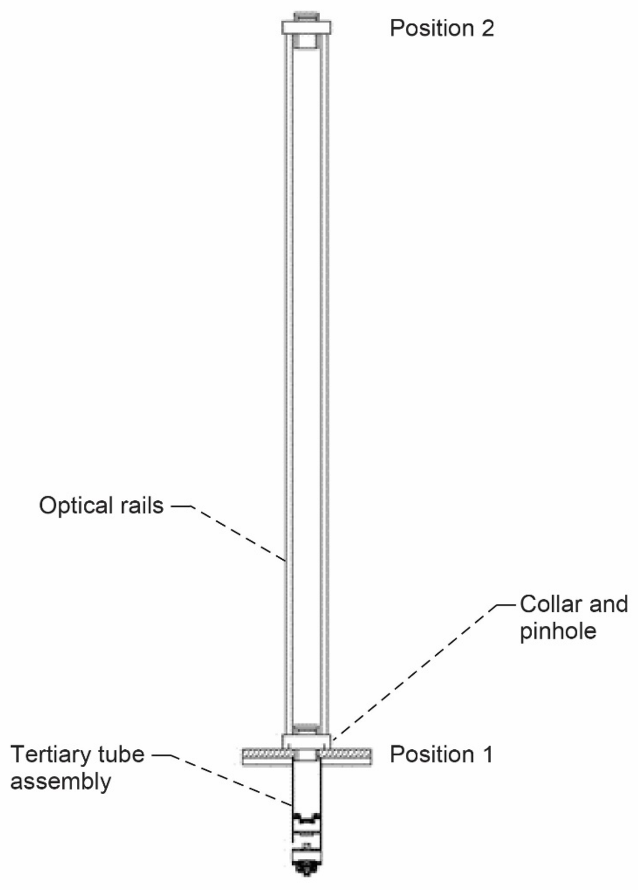

Figure 9.—Tertiary tube alignment tower.

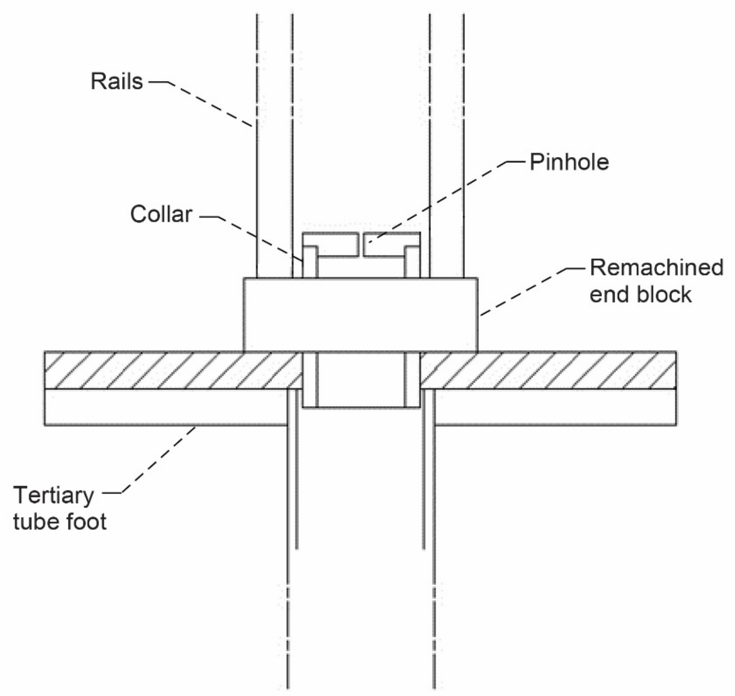

Figure 10.—Alignment collar and pinhole.

Located at each end of the tower are blocks or rings to hold the alignment collar and pinhole. This feature is shown in detail in Figure 10. In this case, the bores of these blocks were remachined to ensure proper centration. This was accomplished using a coordinate measuring machine to locate center by virtue of a best-fit circle relative to the four corner rails. The reported centration error of this circle is less than 2 μm, but it is noted that a larger error is represented by the runout of the rails themselves. At present, this error has not been quantitatively determined or compensated for.

A collar is diamond turned to fit into the remachined rail end block. A pinhole disk is similarly machined to nest into the end of this collar. As previously noted, commercially available pinholes have unacceptably large centration errors, so this pinhole can be microdrilled into the plate as a single assembly, or a commercial pinhole cemented onto the plate after centering with the use of a suitably precise alignment microscope.

The collar and pinhole are installed into position 1 as indicated in Figure 9. An optical power meter is placed behind the pinhole, and the tilt and centration of the FiberPort used to maximize the transmitted power. The collar and pinhole are then placed in position 2, and the transmitted power again maximized. The pinhole is then sequentially shifted between the two positions and the FiberPort iteratively adjusted to maximize the transmitted power at both locations.

As indicated, the tilt and centration adjustments also affect collimation, so it is desirable to return to Section 4.3 and verify collimation after completing this operation. The various adjustments of the FiberPort can then be secured with the locks provided, or potted in place.

5.0 Conclusion

A procedure has been derived for establishing the initial relative alignment of the Integrated Radio and Optical Communications (iROC) primary and secondary optics, as well as the associated tertiary optics assembly. The intent of this initial procedure is to obtain sufficient accuracy to allow more precise subsequent alignment using techniques such as interferometry or wavefront analysis. As such, the resulting accuracy is only required to be within roughly an order of magnitude of the final target values. As noted, the techniques described here, in fact, meet or exceed the targets for tilt and axial spacing, but fall short by tenfold for centration.

Separate sections are included in order for aligning the relative tilts and centration of the primary and secondary mirrors, and in turn their axial spacing. An additional section describes the alignment of the associated tertiary launch optical assembly. By design, the mating faces between the primary, secondary, and tertiary assemblies are precision single-point diamond turned, and therefore, no additional relative registration or alignment between these two subsystems is necessary.

The required apparatus for performing this procedure is described, including both commercially available and custom-fabricated components. In the case of the former, the essential performance characteristics are specified to allow substitution of other devices as appropriate. Specifications for the latter are given in sufficient detail to facilitate their fabrication.

References

1. Wroblewski, A.C.: Baseline Optical Design of Integrated Radio and Optical Communication System. NASA/TM—2020-5001668, to be published, 2020.