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14. ABSTRACT
This TOP describes the instrumentation and procedures for measuring the on-axis and off-axis Optical Transfer Function (OTF) of direct view telescopic systems in a laboratory environment.

15. SUBJECT TERMS
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US ARMY DEVELOPMENTAL TEST COMMAND
TEST OPERATIONS PROCEDURE

*Test Operations Procedure (TOP) 6-3-044 27 July 2009
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OPTICAL TRANSFER FUNCTION FOR DIRECT VIEW TELESCOPES

This TOP supersedes ITOP 6-3-044 dated 26 April 2005.

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1. SCOPE.

1.1 Purpose.

This TOP describes the instrumentation and procedures for measuring the on-axis and off-axis Optical Transfer Function (OTF) of direct view telescopic systems in a laboratory environment. A list of reference documents containing an in depth mathematical and analytical discussion of OTF theory is provided for information purposes in Appendix A.

1.2 Limitations and Assumptions.

This TOP deals with OTF measurement of direct view (visual waveband, 400-700nm) telescopic sights in a laboratory environment and assumes that the operator has a working knowledge of the principles of optics. It is essential that appropriate guidelines and standard laboratory operating procedures for safety are followed. OTF measurement systems may be proprietary in nature and application specific for quality control in a production environment or constructed from laboratory hardware in-situ to suit a one-off measurement application. Use of this TOP will therefore be subject to test equipment variations and test item configuration. The references contained in Appendix A are for information purposes only and to aid understanding of the test methods to be applied.

2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

Item	Requirement
Optical laboratory	Adequate environment control. Standard equipment to include low vibration environment, lighting to optical darkroom standards, rigid optical tables (ideally with all-round access) and a comprehensive range of optical benches and accessories.

2.2 Instrumentation.

Device	Requirement
Object Generator	See section 3.6.2
Image Acquisition System	See section 3.6.4
Image Processor with analysis software	See section 3.6.5
Optical Bench	See section 4.1.3
Mounting Fixtures	As required
Alignment Periscope	See section 4.1.6

3. REQUIRED TEST CONDITIONS.

3.1 Pre-test Planning.

a. Test Plan: Prior to initiating the test program, a test plan must be prepared. The test plan shall:

(1) Describe each test to be performed in sufficient detail to be understood by test personnel and approving authorities.

(2) Describe the measurements to be made, the test criteria, and the data reduction and analysis techniques to be used.

(3) Describe the test set-up for each sub-test and the instrumentation to be used.

b. The test plan shall also include:

(1) Adequate safety procedures for test personnel.

(2) A brief to test personnel on all aspects of the test program, including the purpose of each test, the measurement requirements, and the preparation and operation of all test instrumentation.

(3) All test item and instrumentation operating instructions and safety procedures.

3.2 Preparation.

3.2.1 Facilities.

Preparation of test facilities shall include:

a. Adequate lead time to ensure the facility will be available for the duration of the test program.

b. Assurance that facility environmental equipment is in proper operating condition.

c. In terms of laboratory requirements, conformance to optical darkroom standards is essential, as is good floor stability, although extreme levels of vibration damping are not normally required. The working area should provide easy access to all parts of the OTF system.

d. If the laboratory area is normally clean and dry, clean room conditions (air conditioning, temperature dust and humidity control) are not required. An ambient temperature of 20°C to 25°C and a relative humidity of about 50% are generally satisfactory.

3.2.2 Instrumentation.

a. Prior to initiating the test program:

(1) Ensure that all test instrumentation is in proper operating condition.

(2) Ensure that test personnel are adequately trained to operate the test instrumentation.

(3) Ensure all test instrumentation is available for the test program.

(4) Ensure that the calibration of all test instrumentation is current and will extend through the test period.

(5) Ensure that the accuracy of all test instrumentation will meet the test requirements with adequate measurement uncertainties.

b. The use of automated test instrumentation should be considered during the test planning process.

c. Specific test instrumentation requirements are listed in the individual test procedures.

Ensure that the accuracy of all test instrumentation will meet the test requirements. This is referred to as Test Accuracy Ratio (TAR) of the measurement parameter.

3.2.3 Test Item.

a. Prior to initiating the test program:

(1) Inspect the test item for damage, completeness, deterioration, or manufacturing defects.

(2) Ensure that the test item is in proper operating condition.

(3) Ensure that operating manuals for the test item are available.

b. Test personnel shall be adequately trained to operate the test item and be familiar with all operating modes and controls.

3.3 Data Requirements.

a. The following general data are required for each test performed:

(1) Laboratory environmental conditions.

(2) Participating observer's names, identifiers and their visual acuities if necessary.

(3) Test item settings.

(4) Test item serial number.

(5) Measurement equipment manufacturer, model number, serial number and calibration date.

(6) Drawing of test set-up.

b. Required data specific to individual sub-tests; e.g. calibration, are listed in the appropriate section.

3.4 Description of Test Item.

Provide a description of the test item(s). The description shall include, but not be limited to, the following:

a. A description of the intended use of the test item.

b. A description of each operating mode of the test item.

c. If appropriate, photographs of the test item mounted in the host vehicle (interior and exterior views if possible).

d. The test item specifications for each parameter measured.

e. The physical characteristics (i.e. weight and dimensions) of the test item.

f. A schematic diagram of the test item, its components and its interface to other sub-systems in the host vehicle, if applicable.

g. A description of all control features of the test item.

3.5 Preliminary Remarks.

a. There are many techniques to measure the OTF. The test set-up, instrumentation and methodology used are dependent on the procedure used. It is not practical to detail all methodologies in this document. Therefore, the procedure in this TOP describes a common methodology that scans, records and analyses the image of a line or an edge source. The edge source should be used in those instances when a reticle mark would interfere with the line source scan.

b. The instrumentation used to scan and measure the line spread function (LSF) may be a mechanically moving slit with a detector, or a linear array of detectors that are scanned electronically and aligned to be perpendicular to the line or edge source. The use of an electronically scanned array of detectors eliminates sources of error inherent in a mechanical scanning system. In the test procedure described, it is assumed that an electronically scanned array of detectors is used. The array may be a one dimensional linear array or a two dimensional array. Typically, a linear array with 256, 512, or 1024 elements is used.

c. The procedures described assume the measured data are recorded on some media (e.g. magnetic tape or computer disk) for further analysis. While this analysis requires application specific software, it is not practical for this TOP to detail the required computations. However, a general outline of the necessary steps that are required to analyze the data is provided in sections 4.4, 4.5 and 4.6.

d. Note that the point spread function may also be used to obtain OTF data. However, in practical terms this approach is rarely used due to:

(1) The problems of very low light levels on the photo-detector array.

(2) The requirement for a 2D array in the image acquisition system.

(3) The difficulties of creating a true point source.

e. Deviations from the procedure described may be necessary due to available facilities, national regulations, or instrumentation inaccuracies. In these cases, supporting rationale for the deviation is appropriate and may be required in accordance with the note on page 1 of this procedure.

3.6 Instrumentation Configuration.

3.6.1 General.

a. An OTF measurement system configuration is shown in Figure 1. The system consists of the following elements:

(1) The Object Generator.

(a) Light Source.

(b) Filter(s).

(c) Target slit.

(d) Collimator.

(2) The test item with any two of the following specified: angular magnification M0, entrance pupil diameter, and exit pupil diameter.

(3) The Image Acquisition System

(a) Exit pupil aperture.

(b) Decollimator.

(c) Relay lens (optional).

(d) Detector array.

(4) Image Processor.

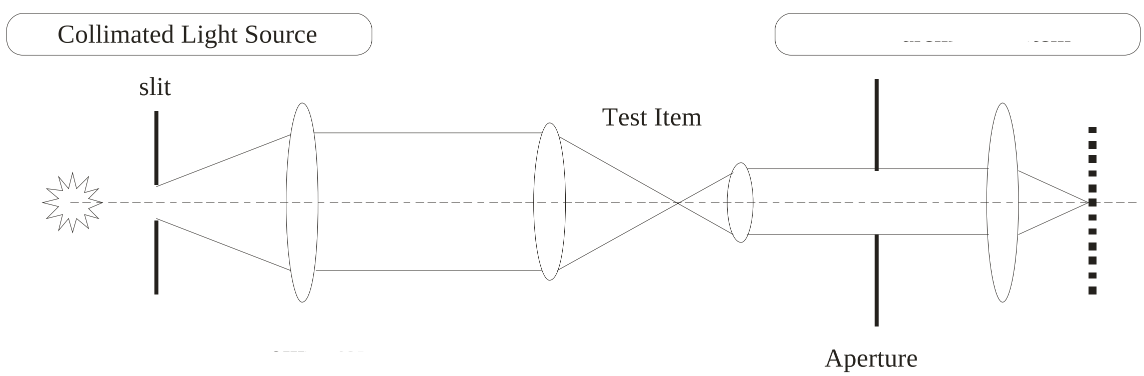

Figure 1. Generic OTF Set-Up

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b. The configuration shown schematically in Figure 1 represents that of most commercially available systems and will be the recommended system configuration described in this TOP. The following sections will discuss each of the system elements.

3.6.2 <u>Object Generator</u>.

a. Light Source.

(1) A light source suitable for use with a silicon photo-detector array is a tungsten halogen lamp at a color temperature of approximately 3100K.

(2) The radiant power and spectral distribution of the light source (to include any filters) shall be such that the peak intensity of the final image on the photo-detector array provides adequate signal-to-noise ratio without clipping. This condition must apply to all test wavebands.

(3) The source should be used with a power supply having a regulation of typically better than 0.2% and a peak to peak ripple of less than 50mV.

b. Filter(s).

(1) Filters for 450, 550, and 650 nm (all at ± 10 nm) with a full width, half maximum band width of less than 40 nm shall be available. Other filters may be used if the OTF is specified at a particular wavelength. The filter parameters should be recorded.

(2) If the OTF is not specified at given wavelengths, or if it is specified for white light, the system shall be configured for an overall photopic/scotopic response; i.e. the spectral characteristics of the light source, collimator, filters, decollimator and detector elements should be taken into account to produce an overall system response corresponding to the photopic/scotopic curves (see Appendix A for the definition of the photopic and scotopic filters).

c. Object Slit.

(1) The object slit is positioned in the focal plane of the collimator that produces the object slit source at infinity for the OTF measurement system.

(2) The object slit may be adjustable or fixed in width. The aspect ratio (length/width) should be greater than 100. The width of the slit should not vary more than 5% over the length of the slit and the slit edges should be free from defects. A fixed width air slit is recommended because the slit parameters are constant and can be precisely controlled.

(3) The critical slit parameter for an OTF measurement system is the slit width. Theoretically it is desirable to have an infinitely thin slit width, although in practice, the slit must have a finite width to allow sufficient light through the system. For a collimator focal length of fc, a test item entrance pupil diameter D, and the measurement wavelength □, the required object slit width w, is given by:

$$w(\mu m) \le \frac{\lambda(nm) f_C(m)}{2D(mm)}$$

NOTE: The equation indicates that the first zero of the angular spatial frequency content of the object slit at the test item should be at least a factor of 2 greater than the cut-off frequency of the test item. The angular spatial frequency content of the object slit is given by sinc(sw/fc), where the first zero is given by s = (fc/w) (cy/mr). The cut-off frequency of the test item in cy/mr in object space is given by D/λ (see definition Appendix A).

d. Collimator.

(1) The collimator projects the object slit to infinity and can be considered as the source or generator of spatial frequencies. This system provides the input to the test item.

(2) The collimator should be diffraction limited and its aperture should be sufficient to over-fill the test item entrance pupil diameter (by typically > 20%) and to avoid vignetting under all envisaged off-axis conditions. This will ensure the cut-off frequency (see Appendix A) of the collimator is greater than the theoretical cut-off frequency of the test item. Typical values for refracting type collimator aperture diameters are 50-100 mm. (An off-axis parabolic reflecting mirror is recommended for collimator apertures greater than 100mm).

(3) The geometric aberrations of the collimator over the test item entrance pupil should be used as part of the OTF measurement uncertainty analysis of section 5.2 when they are considered to be significant in relation to those of the test item.

3.6.3 Test Item.

a. The test item for the purposes of this TOP is a direct view telescopic system with an angular magnification M0 and entrance and exit pupils whose diameters are known or can be established.

b. The cut-off frequency of the test item should be estimated from theoretical calculations or extracted from the test item specification. The cut-off frequencies of the collimator and decollimator should be greater than the cut-off frequency of the test item. If this is the case, the test item will establish the cut-off frequency of the measurement set-up. This will ensure that the full range of spatial frequencies transmitted by the test item is utilized.

3.6.4 Image Acquisition System.

a. Exit Pupil Aperture.

(1) An aperture with a similar diameter to the exit pupil of the test item, (typically 5-10 mm), shall be positioned at the test item exit pupil. This aperture defines the entrance pupil of the decollimator.

(2) The purpose of the aperture is for stray light suppression.

b. Decollimator.

(1) The decollimator produces the final real image of the object slit. This image is focused onto the linear detector array, such that the axes are perpendicular. The decollimator can be considered as creating an image of the object slit from the spatial frequencies transmitted through the test item.

(2) The decollimator should be diffraction limited and its aperture should be sufficient to exceed the test item exit pupil diameter (by typically 100%) and to avoid vignetting under all envisaged off-axis conditions. This will ensure the cut-off frequency (see Appendix A) of the decollimator is greater than the theoretical cut-off frequency of the test item (see paragraph 3.6.3.b).

(3) When the eyepiece focus setting of the test item is set for a non-afocal condition; e.g. a setting of -1 diopter, the distance from the decollimator to the image on the detector array will not be equal to the decollimator focal length, since the final image in the test item is no longer at infinity. In this case the actual distance should be taken as the effective focal length of the decollimator and used when calculating the f-number of the test item/decollimator combination.

(4) The geometric aberrations of the decollimator over the test item exit pupil should be used as part of the OTF measurement uncertainty analysis of section 5.2 when they are considered to be significant in relation to those of the test item.

c. Relay Lens.

(1) A relay lens may be used to project the real image of the decollimator onto the detector array. The use of the relay lens provides some additional control of the image size on the detector array. This may be desirable if the available collimator and decollimator focal lengths produce an image that is too small. High quality microscope objectives are typically used for this purpose.

(2) The numerical aperture of the relay lens shall be large enough to accept the full cone of light from the decollimator. The true magnification of the relay lens must be known and will be based on a fixed image distance, (typically 160mm for a microscope objective).

(3) The object slit criteria defined in section 3.6.2.3 shall be observed.

(4) The geometric aberrations of the relay lens should be used as part of the OTF measurement uncertainty analysis of section 5.2 when they are considered to be significant in relation to those of the test item.

d. Detector Array.

(1) The detector array provides the means to sample the slit image. A linear array (e.g. a Reticon camera) is required. The array should have at least 256 elements with arrays of 512 or 1024 elements being typical. Detector elements should be equally spaced and of constant size. Detector element size is typically 8-25 μm square.

(2) The detector output should have a linear dynamic range of at least 1000 to 1.

(3) If the OTF system is to provide a photopic/scotopic measurement, the detector response must be known and accounted for in the overall system response (see section 3.6.2.2).

(4) The detector sensitivity should be adequate to provide a usable signal to noise ratio over the desired spatial frequency range.

e. Set-Up Constraints. It is recommended that the detector pixel size, decollimator focal length and the optional relay lens magnification are chosen to meet the following requirements:

(1) The test item cut-off frequency corresponds to at least two detector pixels (sampling theorem).

(2) The line spread function does not extend beyond the length of the detector array.

(3) Unless otherwise dictated by the needs of a specific OTF system, it is recommended that:

$$\frac{d}{M_r f_{dc}} << \frac{M_0 \lambda}{2D}$$

where d is the detector pixel size,
M_0 is the magnification of the test item,
M_r is the magnification of the relay lens (microscope objective),
f_{dc} is the focal length of the decollimator,
λ is the measurement wavelength,
D is the diameter of the test item entrance pupil

3.6.5 Image Processor.

a. The image processor system provides the user interface to the OTF system. The user enters various set-up system parameters needed for the OTF measurement. Typical input parameters are:

(1) Collimator and decollimator focal lengths in mm.

(2) Test item magnification.

(3) Measurement wavelength (typically the peak and full width half maximum bandwidth of the spectrum transmitted to the test item).

(4) Test item exit pupil diameter or f-number of the decollimator.

(5) Relay lens magnification (if used).

(6) Slit width in μm.

(7) Detector width in □m.

b. The image processor uses the detector output to provide several operating and display functions. These typically include:

(1) Displaying the position of the final image on the photo-detector array. This display usually enables the detector system integration time to be adjusted such that the amplitude of the LSF is maximized, but within the dynamic range of the detector. This is useful in optimizing the system set-up.

(2) Displaying the line spread function in real-time and its position on the photo-detector array.

(3) Recording one or more line spread functions for later analysis.

(4) Calculating and using correction factors for the small differences, if any, in element to element response.

(5) Correcting for a non-centered line spread function.

(6) Calculating the MTF and PTF.

(7) Applying correction factors for system parameters (e.g. a finite slit width or detector width) and system calibration.

(8) Providing real-time displays of the MTF and PTF in both graphical and tabular form.

4. TEST PROCEDURES.

4.1 Test Set-Up (On-Axis).

4.1.1 Introduction.

a. Proper location, environment and set-up procedures for an OTF measurement system are essential for obtaining accurate and consistent results.

b. The set-up procedures described in this section are those related to a system of the type shown schematically in Figure 2 and are intended for general guidance. Some aspects are appropriate to the setting up of any modern OTF measurement system, although modifications to the described test procedures may be required, to suit available facilities and the nature of the test item. The selection of slit width, collimator/decollimator focal lengths and apertures etc. is described in section 3.6.

c. Subject to the physical constraints of the test equipment layout (see section 4.1.2), a periscopic test item may be oriented in a manner similar to that in the host vehicle (i.e. vertical) throughout the OTF measurement. However, if needed, the test item may equally be laid on its side (subject to correct operation and adequate support) to facilitate OTF measurement without the need for an auxiliary alignment periscope. This may significantly reduce set-up, alignment and calibration problems.

4.1.2 Outline Description.

a. The opto-mechanical assemblies that form the system in Figure 2 are mounted on a rigid, high quality optical bench and comprise:

(1) A securely mounted collimator with a uniformly illuminated slit located at its focus, to form an object located at infinity. For a lens type collimator, a tube mount is recommended. For a reflecting collimator the mounting is critical to preclude distortion of the reflecting surface. It is recommended that the mirror be procured pre-mounted. The collimator-target combination constitutes the object generator (OG).

(2) A high precision front surface reflecting periscope to transfer the optical axis of the object slit to be coincident with the optical axis of the test item. This item is not required when evaluating a co-axial telescope.

(3) A decollimator to provide a real final image of the object slit seen by the test item. The decollimator is carrier mounted to provide linear adjustment in orthogonal axes. Note that the decollimator may be used to produce the final image directly, or when in combination with a relay lens (typically a high quality microscope objective); section 3.6 refers.

(4) An image acquisition unit, for sampling the final image of the object slit; i.e. the line spread function. The unit houses the linear photo detector array, associated electronics and optics for viewing the image formed by the decollimator. This unit is again carrier mounted to provide linear movement in orthogonal axes.

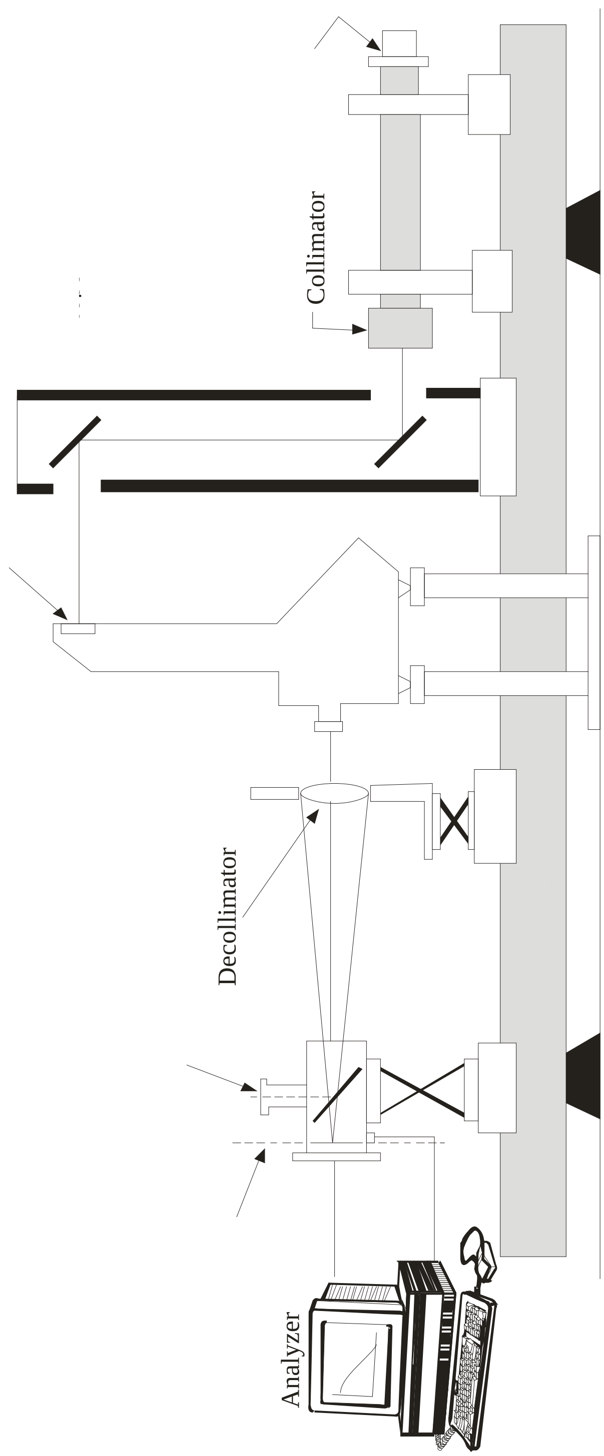

Figure 2. OTF Test Set-Up.

b. A suitable computer, monitor and printer are located adjacent to the optical bench and the image acquisition unit is connected directly to the computer.

4.1.3 Optical Bench, Accessories and Environment.

a. The optical bench provides the basic stability for the overall system and should thus be carefully selected. The stabilized cast iron lathe bed type, typically 2-3 m long, provides adequate support for mounting the various assemblies. Precision (cast iron) carriers are ideal for use with this type of optical bench and a roller bearing carrier is particularly suited for mounting the image acquisition system when aligning and focusing the final image onto the photo-detector array (see section 4.1.9).

b. However, because of the combined size and weight of some vehicle mounted sights, a special mounting fixture, perhaps including a periscopic system may be required. It is normal to mount the set-up on a laboratory type cast iron or granite surface table to obtain adequate stability and freedom from vibration.

c. For a horizontal periscopic test item, two separate optical benches will be required (one in object space, one in image space) to accommodate the offset in the object space and image space optical axes.

4.1.4 Object Generator (OG).

a. The precision slit that forms the object for the test item must be uniformly illuminated by the tungsten halogen light source. To achieve this condition, the lamp filament may be placed at the focus of a concave mirror and on the optical axis of an adjacent bi-convex condenser lens. By adjusting the tilt of the mirror with respect to the lamp filament, a condition must be obtained where the light emerging from the condenser lens completely and uniformly illuminates the object slit. Alternatively, an integrating sphere illumination system may be used.

b. The object slit, together with its illumination system must be located co-axially in the finite conjugate of the collimator such that the plane of the slit lies at the focus of this collimator to within 0.1% of its actual focal length. For a lens type collimator, it is recommended that the lens and object slit be mounted at opposite ends of a precision circular section tube, machined to locate the reference flanges of the lens and the object slit within the required tolerances. For an off-axis reflecting collimator, great care must be exercised to align the target slit in the focal plane of the reflecting element and perpendicular to its optical axis.

c. Other features required of the OG are:

(1) To provide a means of inserting and removing optical filters (typically 50 mm square or 25 mm diameter) between the light source condenser and the object slit.

(2) To provide a means of rotating the object slit (specifically, the center of the slit) about the optical axis of the collimator in a controlled quantitative manner; e.g. using a graduated Vernier circle calibrated in degrees.

(3) To provide a means of changing between different fixed width object slits to match the optical configuration of the system, including the test item.

d. On completion, the object generator should be located in a mechanical supporting system which can be interfaced with the optical bench by means of the precision bench carriers (see section 4.1.3).

e. The supporting system should allow small vertical, horizontal and angular adjustments to be made to the axis of the collimator for alignment with the axis of the optical bench.

4.1.5 Alignment of OG with Optical Bench.

a. The alignment of the optical axis of the collimator with the mechanical axis of the optical bench is a parameter that must be correctly set and maintained prior to taking any OTF measurements.

b. It is assumed that any linearity errors in the optical bench are not significant and that the collimator mounting assembly is placed at one end of the bench and initially set parallel using mechanical measurement.

c. Method

(1) Using a suitable diaphragm placed next to and co-axial with the front element of the collimator lens or mirror, reduce the central aperture to approximately 5 mm diameter.

(2) Using the object generator light source, illuminate the widest object slit.

(3) At the opposite end of the optical bench, position a ground glass screen with a crosshair/concentric circle marking on a bench carrier, such that the projected spot from the collimator is symmetrically positioned about the center of the target screen. (The use of an eye glass can help achieve this condition.)

(4) Slide the carrier over its full travel towards the collimator and observe any displacement of the projected spot.

(5) Using the adjustment in the collimator support system, move the axis of the collimator and repeat the movement of the carrier along the bench until no displacement occurs.

(6) Having achieved this condition, lock the collimator in position and do not disturb.

4.1.6 Alignment Periscope.

a. Depending on the system configuration, an alignment periscope may be used to raise the height of the beam projected from the collimator to the level dictated by the entry window and optical axis of the test item, when that item is periscopic and vertically mounted. The alignment periscope is not generally required for a horizontally mounted test item.

b. The mechanical configuration and degrees of freedom of the alignment periscope are as follows:

(1) Interface with the optical bench is via a bench carrier, to provide movement along the bench and repeatable positioning with respect to the collimator aperture.

(2) The entrance and exit apertures of the periscope should be greater than the full aperture of the collimator.

(3) The lower mirror is normally fixed in position (at 45 degrees) and its centerline and entrance pupil set co-axial with the collimator axis.

(4) The upper mirror is adjustable for height and for micrometer controlled tilt in two perpendicular axes.

(5) Each mirror should reflect the full aperture of the collimator (consistent with overfilling the entrance pupil of the test item).

(6) Each mirror must be front surface reflecting (typically with an aluminum coating) and have a flatness of less than $\lambda/10$ (peak to valley).

(7) To facilitate the OTF measurement of periscopic test items that have a horizontal displacement between input and output optical axes, the alignment periscope should rotate about the horizontal axis of the lower mirror. In practice, this means that the axis that passes through the lower and upper mirrors of the periscope can be tilted away from the vertical to accommodate the horizontal axial displacement within the test item.

c. By using such a periscope, the output axis of the collimator can be adjusted for height and steered to enable virtually any configuration of periscopic test item to be evaluated, without significantly affecting the measured OTF.

4.1.7 Periscope/Test Item Alignment.

a. The following procedure provides a method of establishing the correct relationship between the alignment periscope, the test item and the optical bench:

(1) Mount an auxiliary telescope (typically x3 to x6 magnification and containing a crosshair reticle) on an optical bench carrier fitted with adjustment in the horizontal and vertical axes, and position the telescope so that it is co-axial with the primary collimator.

(2) With the narrowest object slit in the OG illuminated and the telescope carrier at the far end of the optical bench, view the image of the slit through the telescope and adjust the telescope axis to achieve coincidence between the slit image and crosshair. Check that the coincidence condition is maintained over the travel of the carriage.

(3) Place the alignment periscope on the optical bench next to the collimator.

(4) Mount the test item such that its eyepiece axis is parallel and co-planar with the axis of the auxiliary telescope.

NOTE: Due to the weight of a typical periscopic sight, it is preferable to mount the test item on a separate support platform which bridges the optical bench, thus avoiding possible sag due to overloading. Any vibration effects when using this approach must be considered.

(5) Using mechanical aids, set the flange of the test item eyepiece to be square and perpendicular to the optical bench.

(6) With the largest aperture slit illuminated in the OG, adjust the alignment periscope using all required degrees of freedom, to produce uniform and concentric illumination of the test item objective (this will not necessarily mean symmetrical illumination of the test item entry window). Note that the test item periscope mirror may require positioning to achieve normal incidence of the input beam on the sight entrance pupil.

(7) Reduce the slit width in the OG and visually observe its image through the test item eyepiece. At this point in the set-up procedure, the image slit will be close to the center of the field-of-view and should require only minor adjustments. If required, adjust the top mirror of the alignment periscope to position the image in the center of the observed field of view. Ensure that the slit is not coincident with any reticle markings; i.e. the entire slit must be visible. Check that coincidence is maintained over the travel of the auxiliary telescope carrier.

b. It is important that following this sequence of adjustment (alignment periscope and test item) a final check is made to ensure the image of the object slit observed directly through the test item eyepiece is central and unobstructed in the field-of-view.

c. If all above features are correct, the alignment periscope and test item are correctly positioned with respect to the optical bench and must not be moved prior to producing any OTF data.

4.1.8 Decollimator System.

a. The decollimator lens needs to be located in the plane of the exit pupil (EP) of the test item and co-axial with the OTF system axis.

b. To achieve this position, the lens of appropriate focal length should be mounted on an optical bench carrier fitted with height and transverse micrometer movement adjustment. The lens mount is normally screwed into a 90o angle bracket attached to the transverse slide.

c. By projecting light from the OG through the test item and receiving the exit pupil on a screen, the decollimator entrance pupil (typically the lens itself) should be positioned such that its front surface (infinite conjugate side) is as close as possible to the exit pupil of the test item. With the typical EP diameter being 5-8 mm and the typical decollimator aperture being 20-30 mm, adequate concentricity can be achieved by visual observation.

d. It is preferable to use an aperture as part of the decollimator system when very accurate OTF data are required. In this case the stop should take precedence for location in the EP plane with the decollimator located as close as possible behind the aperture. The diameter of the aperture stop should be similar to but not less than the EP diameter.

e. Some final X-Y adjustment of the decollimator may be required once the detector array is in position (see section 4.1.9).

f. A decollimator may be used in conjunction with a relay lens to produce an appropriate final image size on the photo-detector array. Care must be exercised in selecting the numerical aperture of the relay lens to ensure the cone from the decollimator is fully collected. Mechanical mounting of the relay lens must provide the correct linear and co-axial relationships with respect to the photo-detector array.

4.1.9 Detector Assembly.

a. The detector assembly comprises the linear photo-detector array (PDA) and its associated pre-amplifier electronics, an optical viewing unit with movable mirror to enable visual observation of the final image and a graduated rotational stage to allow the PDA to be rotated about its center to maintain the required perpendicular relationship with the object slit. An extension tube can be used to mount a relay lens (microscope objective) to the optical viewing unit.

b. The detector assembly should be mounted to the optical bench in a similar manner to the decollimator system and exhibit the same degrees of freedom (see section 4.1.8).

c. Initial setting up consists of positioning the assembly to be co-axial with the optical axis of the eyepiece and the decollimator. Once this has been set using mechanical measurement, the object slit can be illuminated and the final image from the system produced by the decollimator or relay lens can be received on the PDA and set at 90° to the array axis by use of the graduated circle.

d. By using the movable mirror in the optical unit, the image of the object slit can be visually observed and assessed for position with respect to a crosshair reticle in the viewing unit eyepiece.

e. To check the alignment, first move the PDA carrier to the position of the best observed focus of the final image and adjust the horizontal and vertical movement to position the image on the crosshair. Then slowly move the PDA carrier either side of the focus position and note any displacement of the image.

f. If the defocused image moves off the crosshair and all other components of the overall system are in adjustment, use small movements of the decollimator lens to produce the no-displacement condition.

4.1.10 Final Checks.

a. A final check on the alignment of the complete OTF system can be made by observing the behavior of the final image in both tangential and radial planes. In a correctly adjusted system, both images should be centered in the image analyzer viewing unit and exhibit no displacement about the crosshair when the analyzer carrier is moved either side of the best focus position.

b. It may be possible to use the real-time PTF display to check the final alignment prior to making the OTF measurement. By means of small angular movements of the test item, obtain the configuration that minimizes the PTF error over the largest portion of the spatial frequency range.

4.1.11 Measurement Parameters.

a. Measure the test item on-axis OTF with the object slit in the vertical (tangential) orientation, in accordance with sections 4.4 and 4.6.

b. An additional measurement of the test item on-axis OTF with the object slit oriented horizontally is advisable (photo-detector array vertical). In a well corrected test item, the two orientations will yield comparable results. If the results differ by more than 10%, further investigation of the test item performance or system alignment should be considered.

4.2 Test Set-Up (Off-Axis).

4.2.1 Introduction.

a. This section defines the set-up procedures to be used when making radial and tangential OTF measurements on telescopic systems for the off-axis condition; e.g. when the OTF is to be measured at say, 70% of the field of view, in addition to the on-axis test.

b. The off-axis convention used in this TOP is for rotation of the object generator and image analyzer in the yaw axis; i.e. to left and right of the on-axis condition. The procedures apply equally to pitch axis rotation; i.e. above and below the on-axis condition, the only difference being 90o rotation of the object slit to obtain radial and tangential OTF.

c. The procedure described may be applied to any telescopic system but since the testing of periscopic sights requires some additional modifications, the setting up process is written for this last case. Where appropriate, reference is made to the parts of section 4.1, which apply equally to off-axis testing.

d. For the purposes of this TOP only, the case of parallel object space and image space optical axes will be considered. If the test item has an eyepiece whose optical axis is not parallel to the object space optical axis, modifications to the set-up will be necessary. It is recommended that these modifications, such as additional test fixtures, be made on the image side of the test item. This will reduce the complexity of the set-up procedure.

e. The following procedures assume that the test item is mounted vertically and that the object slit is oriented vertically during the initial on-axis set-up. When the object is rotated in the yaw axis this will provide the correct target orientation to measure the radial OTF. By rotating the target slit and the detector array by 90°, thereby retaining their relative orientation, the tangential OTF can be measured. See the definitions of radial and tangential OTF for clarification of the slit orientations when measuring off-axis OTFs.

4.2.2 Outline Description.

a. The general assembly of the OTF system described in section 4.1.2 and illustrated schematically in Figure 2 still applies, but with a range of modifications depending on the method used for creating the off-axis condition.
Four methods for achieving the revised system layout are as follows:

(1) Method (a) shown in Figure 3 relies on obtaining the yaw field angle in object space (OS) by rotating a high quality (flatness and figure) plane mirror about a vertical axis by half the required angle, to steer the collimated beam from the object generator into the entrance pupil of the test item. This approach is more suited to co-axial test items; e.g. standard telescopes, binoculars etc. and cannot be easily applied to periscopic systems.

(2) Method (b) shown in Figure 4 produces the yaw field angle in object space by rotating the whole object generator about a vertical axis passing through the entrance pupil of the test item. This approach necessitates an independent optical bench (housing the object generator) incorporating a rotational axis which can be located to suit a variety of test item entrance pupil positions. It is compatible with both co-axial and periscopic test items, but in the case of a periscopic system the alignment periscope must be positioned on the same optical bench as the object generator.

(3) Method (c) shown in Figure 4 produces the yaw field angle in object space by rotating the test item about a vertical axis through its entrance pupil. It is suited to the testing of co-axial and periscopic systems but involves an additional feature in the image space (IS) part of the measurement system compared with methods (a) and (b).

(4) Method (d) shown in Figure 5, produces the yaw field angle in image space by rotating the test item about its exit pupil. It is a method best suited to co-axial test items due to the space required for testing a periscopic sight with offset optical axes (input/output).

b. For each of the above methods for obtaining the object space field angle, a complementary image space arrangement of the decollimator lens and image acquisition unit is needed. The image space arrangement requires an independent optical bench to house the decollimator and image acquisition unit. The optical bench must provide a rotational axis that is perpendicular to the optical axis of the test item and in the plane of the exit pupil. This arrangement enables the off-axis image to be focused onto the photo-detector array.

c. It can be seen that for methods (a), (b) and (d) the rotational axis through the exit pupil intersects the longitudinal axis of the main optical bench. For method (c), the rotational axis must move to one side of the optical axis of the main bench in order to remain in the plane of the rotated test item exit pupil. While this feature can be accommodated, it does require additional design constraints to be built into the OTF measurement system.

d. In the case of method (d), the original on-axis position of the IS optical bench is retained. However, this requires a relocation of the complete OS bench in order to maintain the correct rotational axis about the test item entrance pupil.

e. For the purposes of this TOP, method (b) will be used for a description of the set-up procedures, since it reflects the configuration most suited to both categories of test item and offers the simplest mechanical solution. An example of a set-up for method (b) is shown schematically in Figure 6 and illustrates a top view and side view of the system components.

4.2.3 Optical Benches/System Configuration.

a. The statements of section 4.1.3 apply.

b. The object generator (light source, slit unit and collimator) and alignment periscope, if required, must be mounted on the same length of optical bench. This complete assembly should be located on a platform which has a vertical bearing on the optical center line at its front end, i.e. the alignment periscope end of the optical bench. The object generator end of the bench should incorporate a roller bearing that runs on a circular track at the near end of the platform. The optical bench can thus rotate about an arc whose radius is defined by the distance between bearing and roller, and whose length is defined by the track. The rotation should be calibrated about a central zero to ± 10 degrees (nominal). A schematic of an off-axis measurement system conforming to this method is shown in Figure 6.

c. The decollimator lens and image acquisition unit should be configured in a similar manner to that described in (b). In this case the vertical bearing is at the decollimator end of the optical bench and the rotation should be ± 40 degrees (nominal) about a central zero.

d. Some longitudinal and transverse adjustment may be required to ensure the axes of rotation of the optical benches in (b) and (c) are coincident with the entrance/exit pupil planes of the test item.

e. The mounting for the test item (assuming a complex periscopic sight) should provide a rigid support for its size and weight. For off-axis measurement, the test item mounting system must allow access to the entrance and exit pupil planes such that the rotational axes of the object and image space optical benches can be correctly positioned.

f. For off-axis measurement of OTF, and using the configuration of Figure 4, method b, the measurement system therefore comprises:

(1) The object space optical bench system.

(2) The image space optical bench system.

(3) The mounted test item.

(4) The computer, monitor and printer (paragraph 4.1.2.b refers).

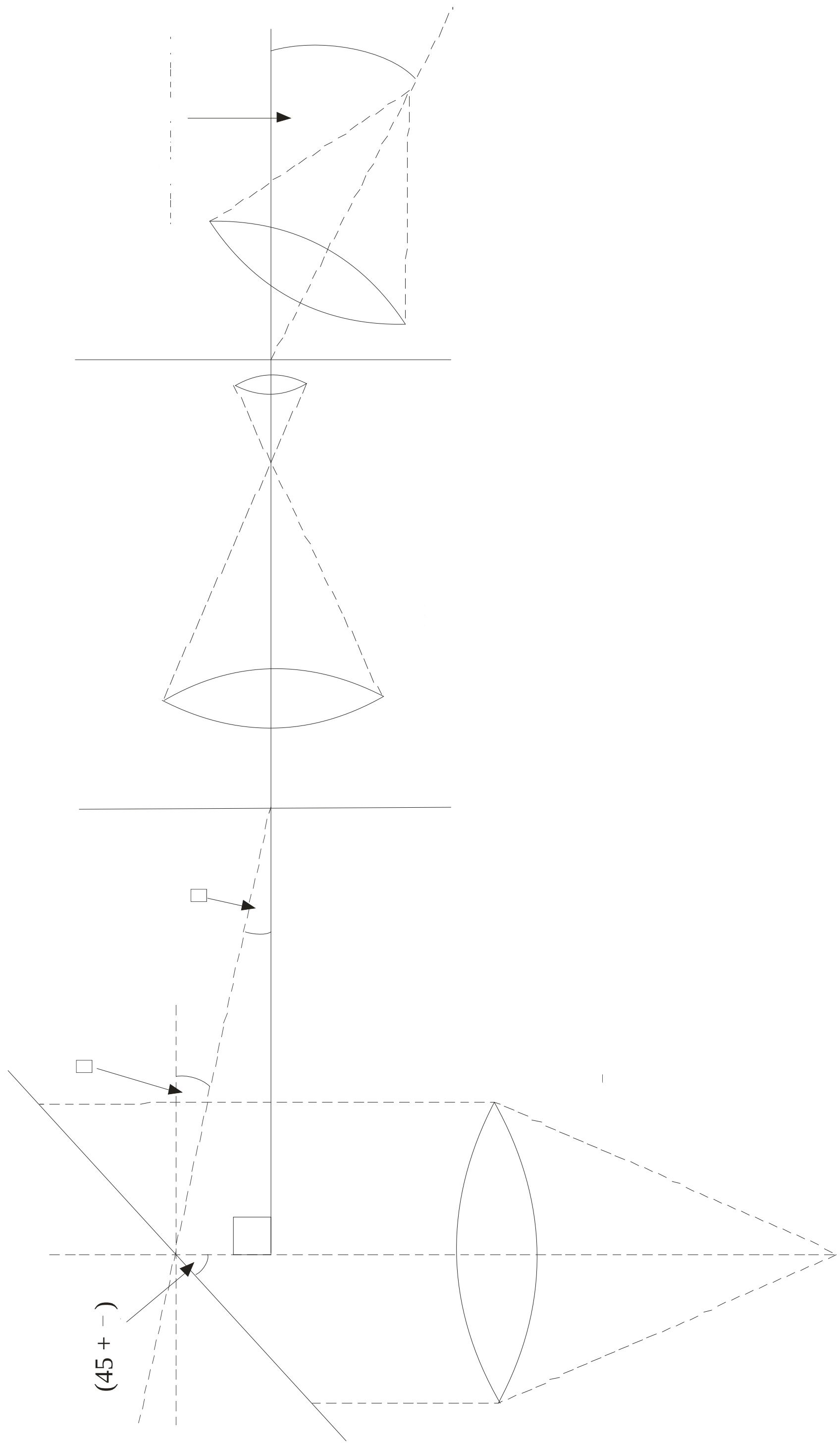

Figure 3. Off-Axis OTF Method (a) – Rotation of Plane Mirror.

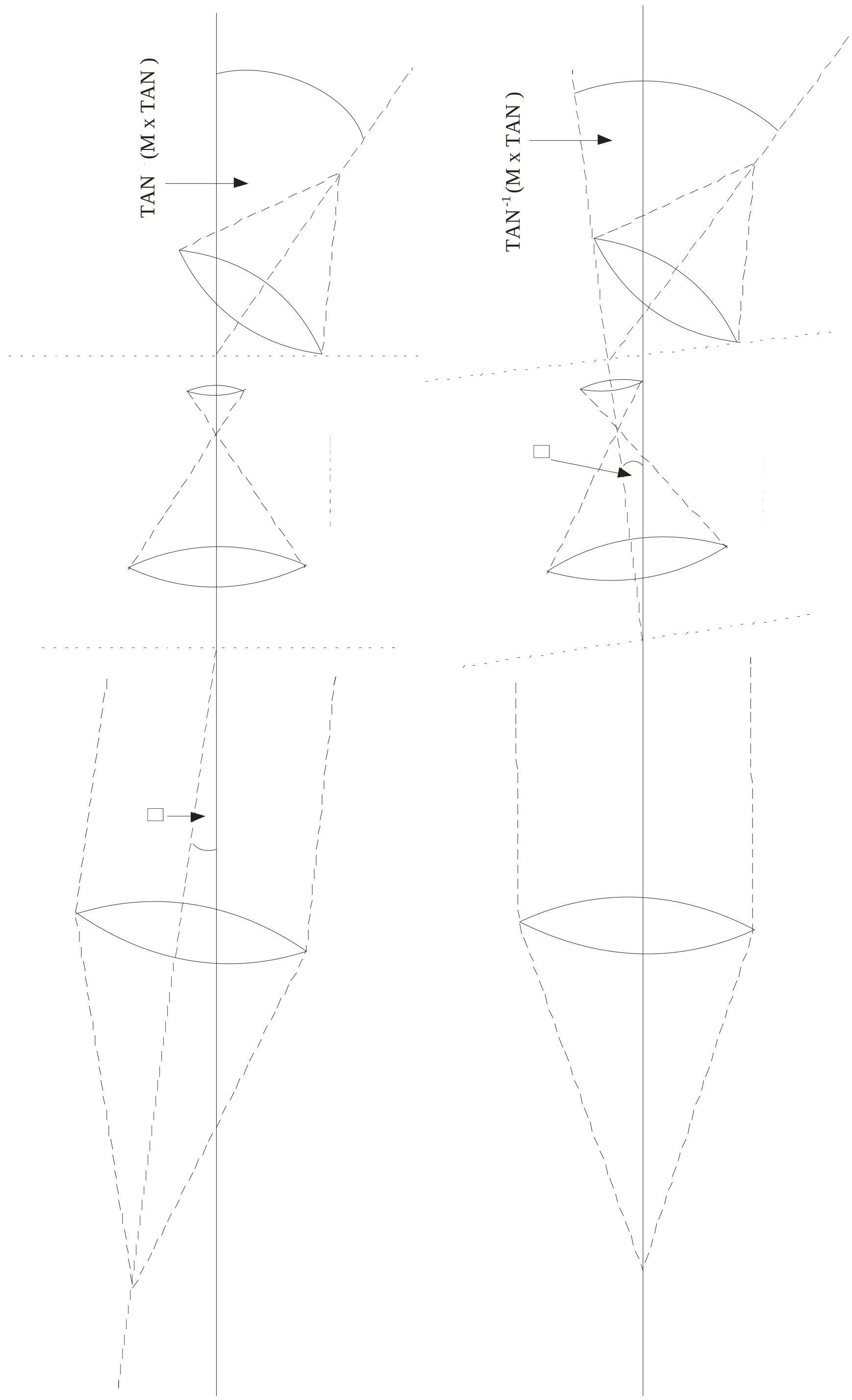

Figure 4. Off-Axis OTF Method (b) and Method (c).

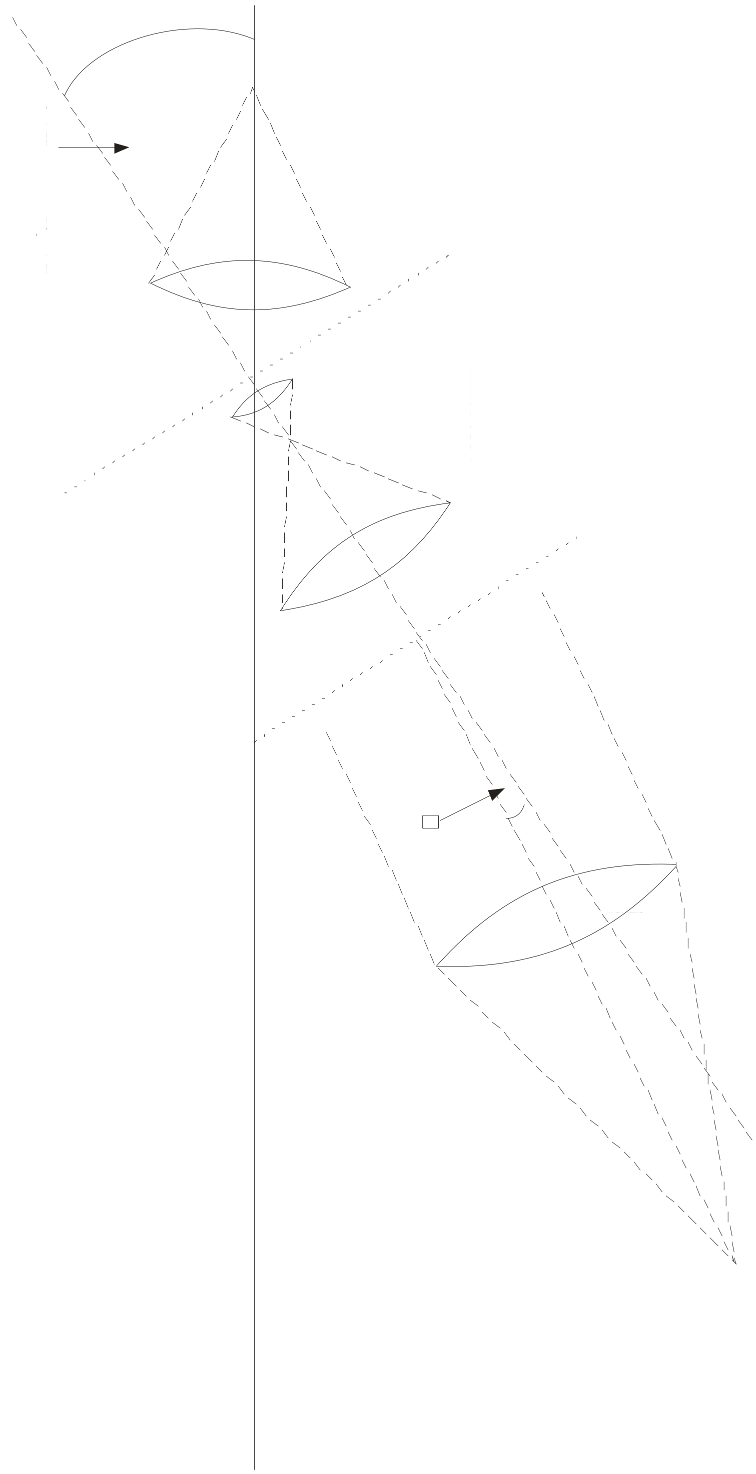

Figure 5. Off-Axis OTF Method (d) – Rotating the Test Item About an Axis Through the Exit Pupil.

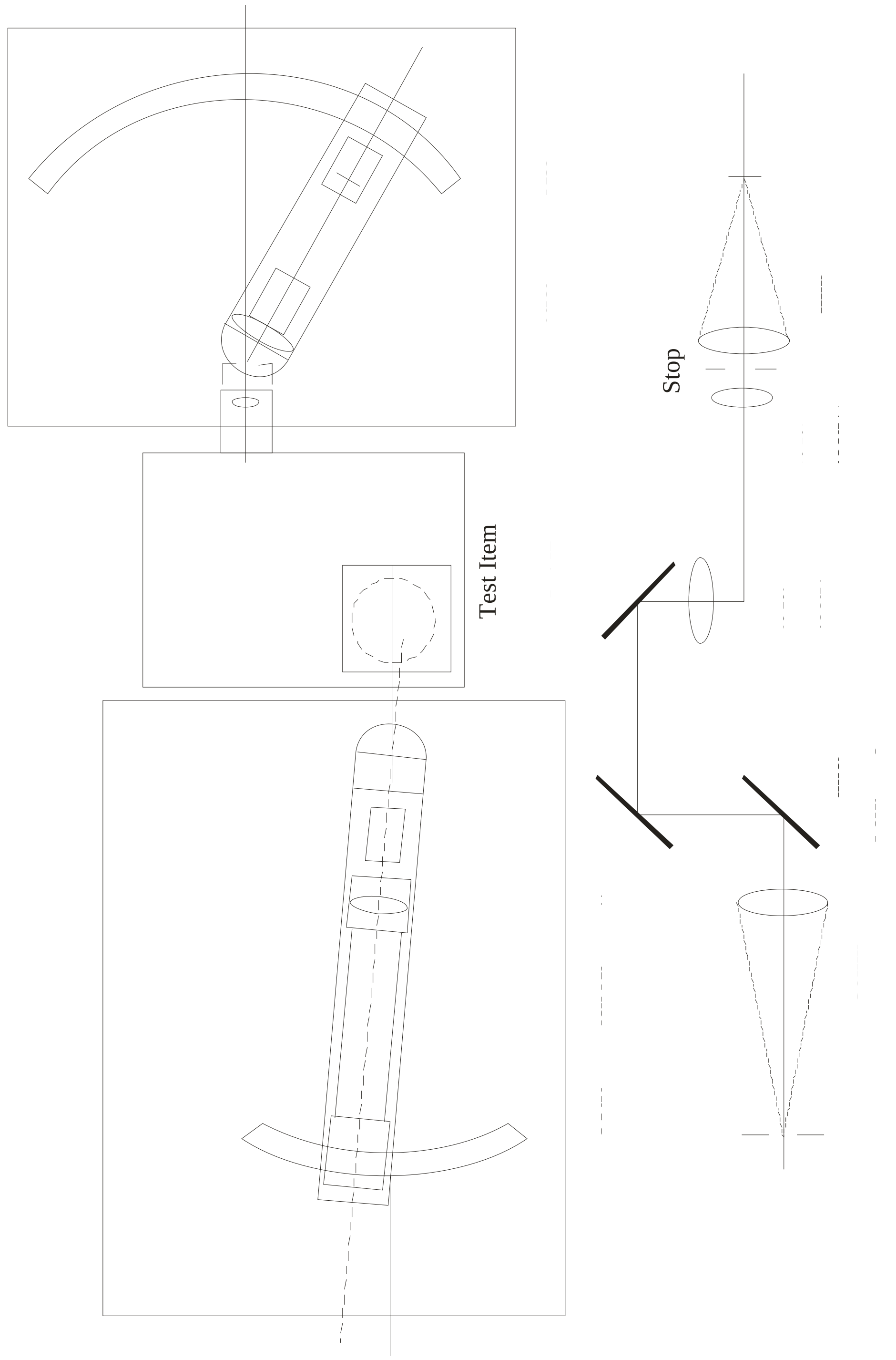

Figure 6. Off-Axis OTF Method (b) – Schematic of System Set-Up.

4.2.4 System Alignment.

a. The following procedure establishes the on-axis relationship between the OS optical bench, test item and IS optical bench and is a pre-requisite for any off-axis measurements. A periscopic test item with co-linear and displaced axes between objective and eyepiece (vertical and horizontal) is considered and represents the worst case for setting up and system alignment. It is assumed that the object generator is aligned with the OS optical bench in accordance with section 4.1.5.

(1) Identify the planes of the entrance and exit pupil of the test item (reference TOP 3-2-838 entitled Direct View Optics) and note their distance from suitable reference surfaces on the sight body or mount.

(2) Place the test item on the laboratory table so that its optical axis is parallel with the table top.

(3) With its rotational position set at zero, position the IS optical bench so that it is mechanically aligned with the eyepiece and its axis of rotation is located diametrically in the plane of the exit pupil. Adjust the height of the bench so that (a) its horizontal plane is parallel with the optical table and (b) the optical axis of the decollimator is co-axial with the test item eyepiece.

(4) With its rotational position set at zero, position the OS optical bench so that it is mechanically aligned (parallel) with the IS optical bench and its axis of rotation is located diametrically in the plane of the test item entrance pupil. Adjust the height of the bench so that its horizontal plane is parallel with the optical table. Note that the height above the surface of the optical table and the horizontal positions of the OS and IS optical benches will be different depending on the configuration of the test item.

(5) Fit the alignment periscope to the OS bench and set the adjustable top mirror to be parallel with the lower fixed mirror. Noting the position of the test item on its mount (so that it can be precisely relocated later), remove the test item assembly from the optical table.

(6) During this stage, the alignment periscope serves to optically connect the axes of the OS and IS optical benches in the absence of the test item. Use the procedure of sections 4.1.7.a. (1) and (2) to optically align the OS and IS optical bench systems, taking care not to disturb their respective centers of rotation. The offset between the OS and IS axes can be accommodated by using the rotation (tilt) and top mirror height (spatial separation) adjustments of the alignment periscope. Do not alter the angular relationship between the upper and lower mirrors of the alignment periscope during this operation.

(7) Carefully replace the test item / mount assembly to its previous position (from paragraph (5)) on the optical table. Use the procedure of sections 4.1.7.a.(4) to (7), 4.1.7b and c to complete the optical bench/test item alignment.

b. Use the procedures described in sections 4.1.8, 4.1.9 and 4.1.10 to complete the set-up for on-axis OTF measurement. It is advisable to make an on-axis OTF measurement at this stage in accordance with section 4.1.11 to check that the result is close to the expected value and to confirm that no major set-up errors have occurred.

4.2.5 Position of Aperture.

In paragraph 4.1.8.d it is recommended that a stop be used at the exit pupil when accurate OTF data are required. For off-axis measurements, the position of the stop is important and for optimum results the stop (rather than the decollimator) should remain co-planar with the exit pupil of the test item. If this condition is maintained and the decollimator clear aperture diameter is much greater than the stop diameter, the requirement for precise coincidence of the center of rotation of the IS bench with the exit pupil is reduced.

4.2.6 Off-Axis Measurement.

a. With the measurement system set for on-axis OTF (OS and IS benches set to zero), rotate the OS bench to the desired field angle. For a periscopic test item whose line of sight (object space optical axis) is directly above its eyepiece axis or where the OS and IS optical benches have been offset to accommodate the test item configuration, the alignment periscope will be vertical. The beam from the output (top) mirror of the alignment periscope will thus pass directly above the center of rotation of the OS bench. When the OS bench has been rotated to the required field angle, the alignment periscope must be adjusted for tilt angle and output mirror height only, to ensure (a) the correct field angle is maintained and (b) the beam entering the test item overfills the entrance pupil, i.e. to avoid vignetting.

b. Having ensured that the image in the test item is in the expected location and is not obscured by any part of the reticle, rotate the IS bench through an angle tan-1 (M * tan θ) where M is the test item paraxial angular magnification and θ is the object space field angle.

c. Ensure the aperture (stop) is correctly positioned at the exit pupil and is of the appropriate diameter as specified in paragraph 4.1.8.d.

d. Position the decollimator close to the exit pupil and align with the image acquisition unit as defined in sections 4.1.8 and 4.1.9 such that the final image is correctly located on the photo-detector array.

e. Produce the required off-axis OTF data as defined in section 5.

4.2.7 Measurement Parameters.

a. With the slit in the vertical position and set at the required field angle in object space, measure the radial OTF in accordance with sections 4.4 and 4.6.

b. Without disturbing the system configuration, rotate the slit and PDA through 90o, check the central location of the slit image in the image analyzer viewing unit and measure the tangential OTF in accordance with sections 4.4 and 4.6.

4.3 Calibration.

4.3.1 Introduction.

To ensure that the data obtained from an OTF system of the type described in sections 3.6, 4.1 and 4.2 are valid, it is essential that calibration procedures are defined and adhered to. This section deals with calibration aspects on a “prior to use” basis and over yearly or longer intervals.

4.3.2 Prior to Use.

a. Modern OTF systems which derive data from the Fourier transform of the line spread function utilize a narrow slit as the object for the test item and typically, a linear photo-detector array for the image analyzer.

b. The software which controls the set-up parameters and performs the mathematical computations for the system normally contains a calibrate function.

c. Once the set-up procedures of sections 4.1 and 4.2 have been completed and the software menu followed for the configuration of the test system, the calibrate functions must be used prior to taking any measurements.

d. Having excluded all light from the photo-detector array, the calibration functions will automatically measure the dark current signals from the array for each of the integration times in turn. All measurements subsequently made will be corrected for dark current signal non-uniformity. This significantly improves MTF measurement accuracy, particularly where long detector integration times are used to acquire the line spread function.

e. The detector array spectral response may vary slightly from element to element. The analyzer system calibration function should provide a means of measuring the response of each detector element and calculating a correction (i.e. calibration) factor for each element prior to and after the test.

4.3.3 Longer Intervals.

At extended intervals (typically 2-3 years) a procedure should be implemented whereby a reference or audit telescope has its OTF independently measured. This reference measurement can be used whenever required to gauge the performance of the complete OTF system for comparison with previous measurements. A comparison of this type should be made prior to a critical test item assessment.

4.3.4 Audit Telescope Parameters.

The audit telescope is used as a calibration test item and its design should reflect as many of the parameters of a typical real test item as possible. As an example, it is recommended that where possible, the magnification and field of view of the audit telescope should be within ± 20% of the same parameters of the anticipated test item.

4.3.5 Calibration Specification.

a. The calibration of the audit telescope should ideally be made by three independent accredited test houses using a test system, test set-up and measurement procedure similar to the subject test system.

b. The following criteria shall be provided to the test house:

(1) The measurement datum plane shall be defined such that the MTF is optimized at a specified spatial frequency. A suitable value for a typical high quality military sight is 4-5 cy/mr in object space.

(2) The limit of the X-axis for the presented data (the maximum spatial frequency required).

(3) The spectral waveband(s) at which measurements are to be made (i.e. filter specifications) or the overall spectral characteristic of the measurement system, e.g. photopic.

(4) The rotary orientation of the audit telescope with respect to any external reference marks.

c. The test house shall provide:

(1) A plot of MTF and PTF from 0 cy/mr to the maximum specified spatial frequency for:

(a) The on-axis condition.

(b) The off-axis condition (if required) at +/- 70% of the field-of-view.

(c) Both radial and tangential OTFs will be provided. The position of the measurement will be identified with respect to the audit telescope reference marks.

(2) The value of the MTF at the specified calibration frequency.

(3) The MTF measurement error.

(4) The value of the area under the MTF curve between 25% and 75% of the cut-off frequency.

4.4 Linespread Function Measurement.

a. A collimated object slit is presented to the test item and is imaged on the detector array. The slit is initially positioned to be at the center of the field of view. Care must be taken that neither the object slit nor the scanning direction are overlapped by any reticle marks within the field of view of the test item. The test item focus and/or the detector position are adjusted to provide the narrowest LSF as viewed visually and on the real time display. Adjust the amplitude of the LSF on the display as described in paragraph 3.6.5.b.(1), noting the following:

(1) The system shall typically scan and analyze at least 20 LSF readings prior to displaying an average LSF. The average LSF will be shifted right or left to place the peak value close to the center of the scan to ensure the full extent of the LSF is captured.

(2) If the slit source and/or the scan are interrupted by a reticle mark, it may not be possible to obtain valid LSF data. The position of the object slit may be adjusted locally to remove the influence of the reticle mark, or if this is not achievable, the use of an edge target may be more appropriate. If an edge target is used, the edge is positioned as close as possible to the desired point of measurement such that it is not interfered with by any reticle mark. The analytical system must take the derivative of the scanned edge function to obtain the LSF. Once the LSF is obtained, the analysis may continue as described above.

b. The OTF of the test item is obtained by performing a Fourier transform of its LSF. The MTF is the modulus of the OTF normalized to 1.0 at zero spatial frequency.

c. Choose a reference spatial frequency near the point of maximum slope of the MTF curve. The analytical system shall be capable of displaying the MTF at the reference frequency. This reference will be used to adjust the alignment of the measurement system so as to produce a maximum reading at that frequency. Move the detector array axially (towards or away from the decollimator) by a small amount and record the MTF. Repeat this procedure several times to obtain the maximum value of the MTF at the reference frequency.

d. After adjusting the system to produce an optimized MTF, record the presented data in both graphical and tabular form. Record the LSF data associated with the optimized set-up.

4.5 Edge Function Measurement.

a. The target source shall be a half-infinite plane such that one half of the object is effectively blocked. The edge of the target source shall be positioned at whatever part of the field of view the OTF is to be measured.

b. Focus the target source onto the detector array. Ensure that the direction defined by the axis of the edge image is perpendicular to the direction of the axis of the linear photo-detector array. Adjust the focus of the image of the edge on the detector array such that the steepest gradient is obtained. The output of the detector array is the edge function. A typical edge function is shown in Figure 7, where the diffraction pattern intensity distribution is shown relative to the intensity of the unobstructed wave (axial notation =1.0).

c. Having adjusted the set-up parameters to produce the edge function with the steepest slope, record more than 20 edge functions and calculate an average function from these values.

d. Determine the derivative of the average function up to the first maximum of the edge function. This may be done in two ways:

(1) By digital differentiation.

(2) By fitting the edge function data to a function of known derivative.

e. The derivative of the edge function thus determined is the LSF. Once the LSF is known, the OTF is calculated as outlined in section 4.6.

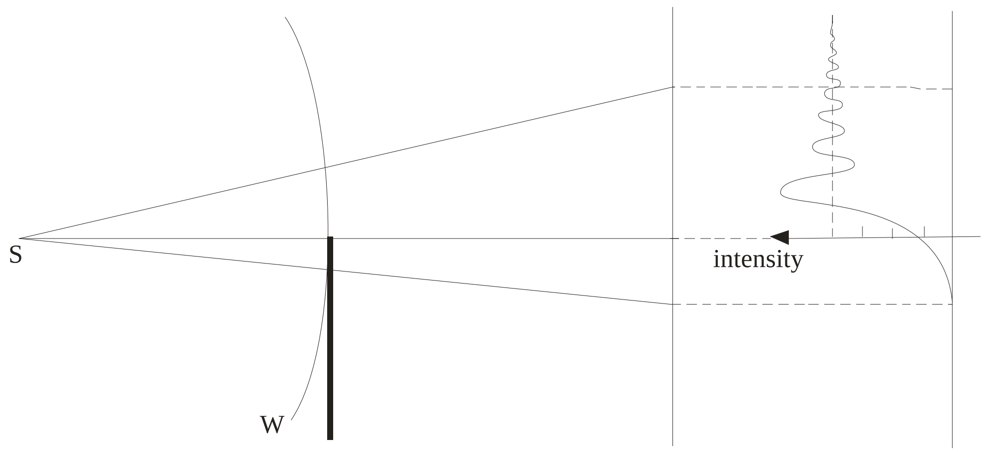

Figure 7. Diffraction Pattern at a Straight Edge.

4.6 Correction of the Measured MTF.

The mechanical and optical characteristics of the target slit, collimator, decollimator, relay lens (if used) and the analyzing detector element, affect the measured MTF. However, the MTF of the collimator, decollimator and relay lens will normally be very close to diffraction limited due to their intrinsic optical quality. The contribution of these elements to the measured MTF of a complex modern AFV sighting system is therefore likely to be insignificant, although this may not be the case for all telescopic instruments.

The contributions to the MTF from the target slit and analyzing detector element must be removed from the measured data in order to obtain the true MTF of the test item. For this process:

Let s denote spatial frequency, w denote target slit width and d denote the width of a detector element:

Then if the corrected MTF of the test item = MTF (s)

And the measured (uncorrected) MTF of the test item = MTFm(s)

$$\text{Then MTF (s)} = MTF_m(s)\left[\frac{\sin(\pi sw)}{\pi sw}\right]^{-1}\left[\frac{\sin(\pi sd)}{\pi sd}\right]^{-1}$$

$$= MTF_m(s)\left[\operatorname{sinc}(sw)\right]^{-1}\left[\operatorname{sinc}(sd)\right]^{-1}$$

Note that s, w and d refer to the same reference plane.

c. In modern OTF measurement systems employing slit targets and Fourier transform data processing, the above calculations are normally carried out automatically by the system software. The system configuration procedure will require the object slit width and detector dimensions as part of the input data, although in the case of a system using a scanning photodiode array, the information on the detector element/pixel dimensions will already be incorporated within the software.

5. DATA REQUIRED.

5.1 System Requirements.

a. A schematic diagram and description of the test set-up.

b. A schematic diagram and description of the test item.

c. The specifications of the components of the OTF measurement system, e.g. collimator type, focal lengths, apertures, alignment periscope dimensions and light source characteristics.

d. A description of the calibration methodology.

e. The quantitative configuration data for the system set-up. This should include but not be limited to the f-number (of the decollimator), the spectral characteristics, target slit width, the data plane, the datum plane, the field angle in object space, the measurement azimuth (radial and / or tangential), the position of any reference mark on the test item, the spatial frequency range of measurement or discrete spatial frequency settings, the focusing criteria and method of optimization and the test item eyepiece setting (if applicable).

f. The scale factors used in the MTF calculation, e.g. the transfer from lp/mm in image space to cy/mr in object space.

5.2 Uncertainty Analysis.

a. Assess the measurement uncertainties by analyzing all systematic and random sources of error in the measuring equipment and the environment in which it was used (Reference ISO 9335). It will be necessary to consider the systematic sources of error relative to the test item characteristics, as well as possible non-linearities or shift variance.

b. Assess the OTF measurement accuracy resulting from the combination of measurement uncertainties.

6. PRESENTATION OF DATA.

a. Prepare a graph of the modulation transfer factor versus the required spatial frequency units (typically cy/mr in object space) as shown in Figure 8. The result is the modulation transfer function (MTF). The diffraction limited MTF of the test item should be superimposed on the graph for reference purposes.

b. Prepare a graph of phase shift in the image versus the required spatial frequency units (typically cy/mr in object space) as shown in Figure 9. The result is the phase transfer function (PTF).

c. A statement of overall MTF/PTF measurement accuracy shall be reported along with the associated level of confidence derived from the combination of all measurement uncertainties.

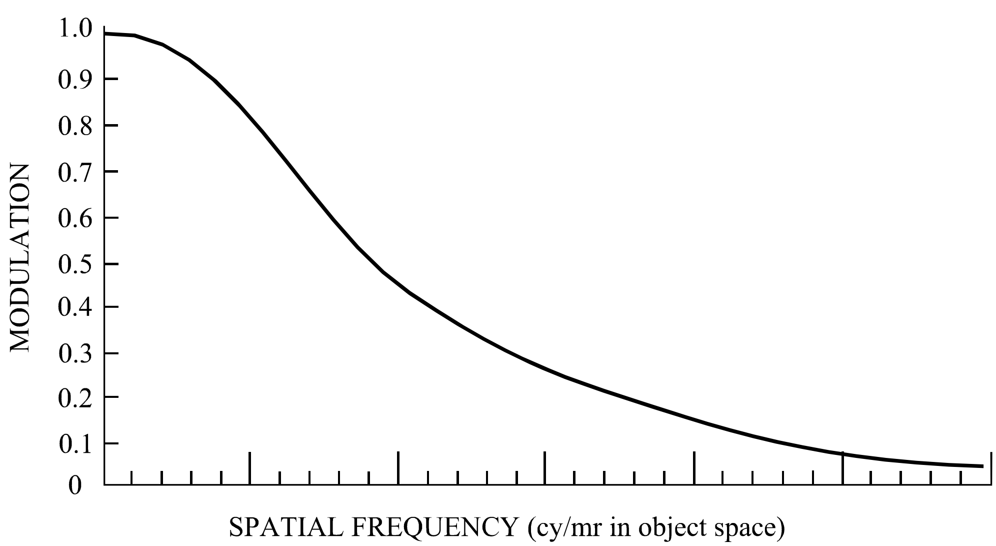

Figure8. Modulation Transfer Function (MTF).

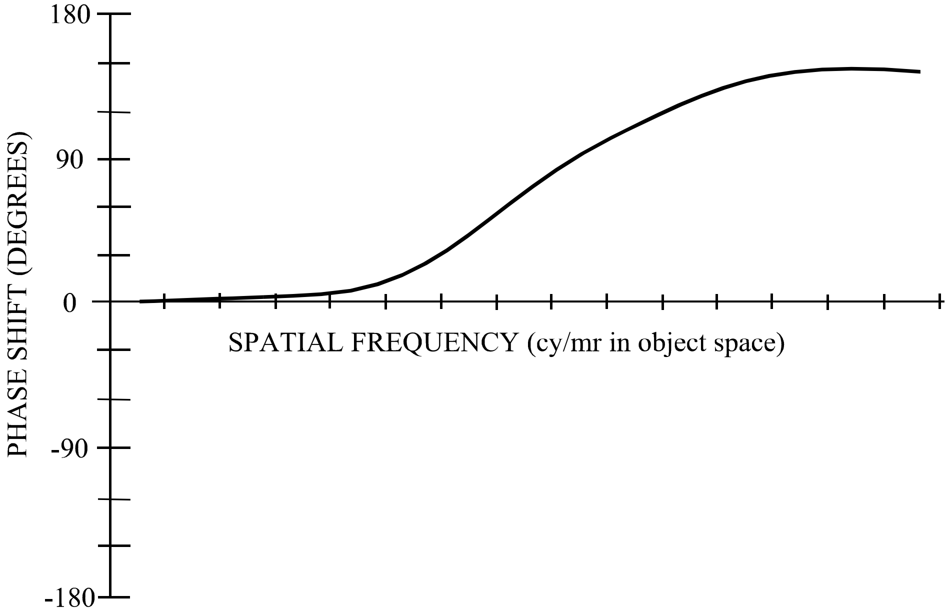

Figure 9. Phase Transfer Function (PTF).

APPENDIX A. DEFINITIONS.

Aberration. Aberration is a defect in an optical system that causes the geometrical image to deviate from the rules of paraxial optics. The primary aberrations comprise spherical aberration, coma, astigmatism, field curvature, distortion and chromatic aberration.

Accommodation (Ocular). Ocular accommodation is the variation of the total refractive power of the human eye that permits the observer to clearly see objects at different distances. The limits of accommodation are the distances of the nearest and farthest points, typically 250mm to infinity, which can be focused clearly. The limits of accommodation vary with age.

Accuracy (Measurement Accuracy). The accuracy of a measurement refers to how close a measured value is to the true value or an accepted value. The difference between the measured value and the true or accepted value is the error. This error is a combination of all systematic and random sources of error in the measurement system. The accuracy of a measurement can never be better than ± half the resolution of the measuring equipment but may be worse.

Afocal System. An afocal optical system has its conjugate points at infinity. For this condition, the eyepiece setting of a telescope must be zero diopters.

Airy Disk. The Airy disk is the area bounded by the first zero or dark ring of the diffraction pattern formed in the image plane of an aberration-free optical element or system with a circular aperture.

Aliasing. The result of a sampling frequency that is too low to preserve the spatial frequencies of the scene being sampled. When the frequency content in a scene is greater than half the sampling frequency, it appears in the sampled scene at a lower (aliased) frequency.

Angular Subtense. The planar angle subtended by an object or image being viewed or projected.

Aperture Stop. An aperture stop is the diameter that limits the cone of rays transmitted by an optical system from an axial point on the object to the corresponding point in image space. The aperture stop is the element whose image in object space is the smallest, as seen from the object.

Collimator. A collimator is an optical instrument consisting of a well corrected objective lens or an off-axis parabolic reflector (typically having a peak to valley wavefront error of less than $\lambda/8$) with an illuminated target object (e.g. a slit or reticle) in its focal plane. A collimator makes an object placed in its focal plane appear to be at infinity.

Collimator f/#. The ratio of the collimator focal length to its effective aperture, e.g. for a 10 meter focal length mirror and a 0.10 meter diameter beam, the f/# is 100.

Collimator Working Distance. The collimator working distance is the maximum distance at which the beam from the collimator fills the entrance pupil of the test item for all points in the test item's field-of view, as shown in Figure A-1.

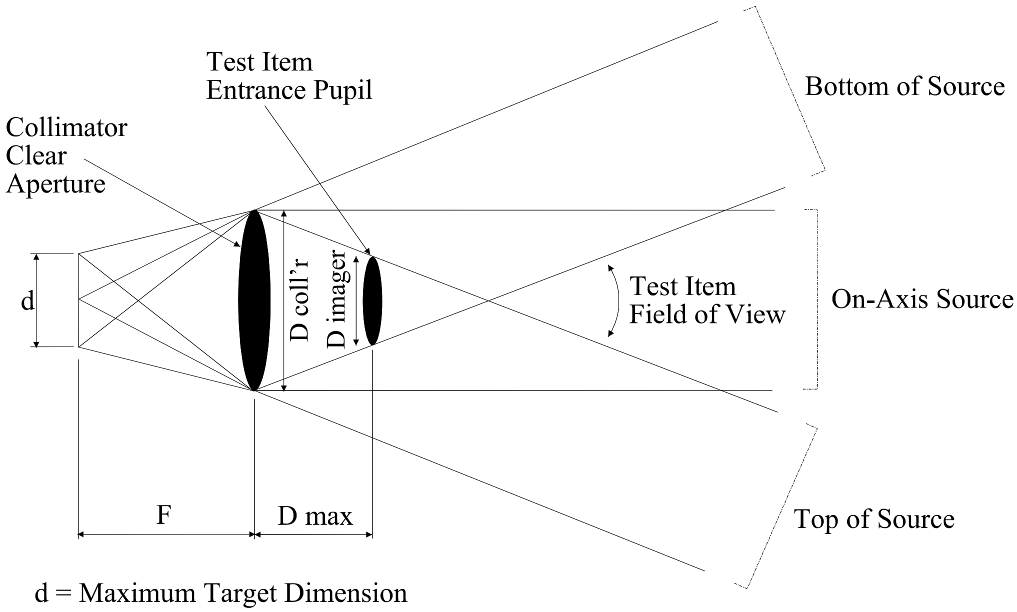

Figure A-1. Collimator Working Distance.

The collimator working distance in meters, D_{max}, is given by:

$$D_{max} = \frac{(D_{coll'r} - D_{imager}) * F}{d}$$

where $D_{coll'r}$ is the aperture diameter of the collimator (mm), D_{imager} is the aperture diameter of the test item (mm), F is the focal length of the collimator (m) and d is the maximum dimension of the collimator target (mm).

<u>Conjugate Planes</u>. Two planes perpendicular to the optical axis of an optical system that contain conjugate points.

<u>Conjugate Points</u>. Two points of an optical system, such that light emitted from the object point will be focused at the image point.

Contrast. The apparent difference in brightness between light and dark areas in an image is defined as:

$$C = \frac{L_T - L_B}{L_T + L_B}$$

where L_T is the luminance of the target and L_B is the luminance of the background.

Convolution. The convolution, g(X), of two functions f(x) and h(x) is defined as:

$$f(x) * h(x) = g(X) = \int_{-\infty}^{+\infty} f(x) h(X - x) dx$$

Correlation. The correlation, $c_{fh}(X)$, of two functions f(x) and h(x) is defined as:

$$f(x) \otimes h(x) = c_{fh}(X) = \int_{-\infty}^{+\infty} f(x) h(x + X) dx$$

Note that when f(x)=h(x), the result is known as auto correlation and when f(x)≠h(x), the result is known as cross correlation.

Cut-off Frequency. The spatial frequency at which the modulation transfer function falls to zero, or, for practical use, below some specified amount such as 3%. The cut-off frequency (f_{co}) for a diffraction limited optical system is given by:

$$f_{co} = \frac{1}{\lambda(\mathrm{mm}) * f_{no}} (\mathrm{cy/mm}) \quad \text{in image space, or}$$

$$f_{co} = \frac{D(\mathrm{m})}{\lambda(\mathrm{mm})} (\mathrm{cy/mr}) \quad \text{in object space}$$

where λ is the measurement wavelength, f_{no} is the f-number, and D is the entrance pupil diameter of the test item.

Data Plane. Data plane is the plane in which the actual OTF measurement is made.

Datum Plane. A datum plane is perpendicular to the optical axis of a measurement system. It is the plane to which all spatial frequencies are referred and thus to which test results may be compared. For a telescope, the datum plane may be at infinity in object space and the spatial frequency of the OTF of the test item expressed in cy/mr.

Decentration. Decentration is any deviation from coincidence between the optical and mechanical centers of an optical element.

Decentration Aberration. An image aberration occurring in an optical system when one or more centers of curvature of the optical surfaces do not coincide with the optical axis.

Decollimator. Decollimator is a refractive or reflective system that acts as an inverse collimator.

Derotation. In a panoramic sight, the image rotates about the optical axis as the periscopic head mirror is rotated relative to the sight body. This image rotation can be removed by the use of additional optical elements within the sight, e.g. a Dove prism. The term derotation is a measure of the system's ability to correct for the image rotation.

Diffraction Limited System. The term diffraction limited implies that the performance of an optical system is limited by the physical effects of diffraction rather than geometrical imperfections in either the design or fabrication.

Diopter. The Diopter (D) is a unit of optical measurement that expresses the refractive power of a lens or prism. The power of a lens, in diopters, is the reciprocal of the focal length in meters. The power of a prism, in prism diopters, is the displacement of a ray, in centimeters, at a distance of one meter from the prism, i.e. 1 prism diopter is the power of a prism that deviates a ray by 1 cm at a distance of 1 meter.

Diopter Movement. The diopter movement, or adjustment, of the eyepiece of an optical system provides accommodation for the eyesight differences of individual observers. The axial movement, x(mm), of an eyepiece with an effective focal length of f(mm), to provide a positive or negative correction of x′ diopters (final image distance measured from the second focal plane of the eyepiece) is given by:

$$x(\mathrm{mm}) = \frac{x'(D) * f^2(\mathrm{mm})}{1000}$$

Distortion. Distortion is an image defect (aberration) in which the magnification is not constant over the field-of-view. For radial distortions, the following polynomial can be used to describe the variation of magnification with field angle (ω):

$$M(\omega) = M_0 + A\omega + B\omega^2 + C\omega^3 + D\omega^4,$$

where M_0 is the paraxial magnification. Distortion indicates the percentage difference in magnification of an off-axis object compared to a paraxial object and can be expressed as:

$$D(\omega) = \frac{M(\omega) - M_0}{M_0} \times 100$$

For example, a negative radial distortion deforms a square grid object into a barrel shape (barrel distortion), a positive radial distortion deforms a square grid object into a pillow shape (pincushion distortion), and projecting an image onto a surface at an angle (keystone distortion). Figure A-2 shows the effect of different types of distortion on a square grid object.

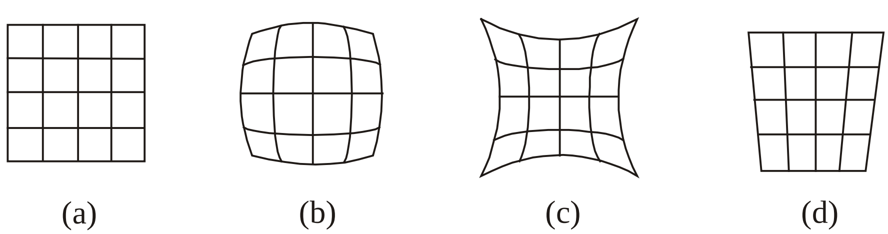

Figure A-2. Examples of Distortion.
(a) Object, (b) Barrel Distortion, (c) Pincushion Distortion, and (d) Keystone Distortion.

Edge Spread Function. Edge spread function is a mathematical representation of the spatial distribution of intensity in the image plane of an edge, in a direction perpendicular to the axis of the edge object.

Entrance Aperture. The entrance aperture is the first physical aperture of the optical system that limits incoming rays parallel to the optical axis. It is typically the mechanical housing of the objective.

Entrance Pupil. The entrance pupil is the image of the aperture stop formed by the optical elements between the aperture stop and the object.

Entrance Window. The entrance window is the first optical element of the optical system intersected by a ray originating from a distant object. In some systems, the entrance window is a protective assembly without optical power.

Erector System. The erector system in a telescope is a combination of lenses or prisms that erect (i.e. bring upright) the primary image produced by the objective for viewing by the eyepiece. An erecting eyepiece is a system combining the erecting optics and the eyepiece optics.

Exit Aperture. The exit aperture is the last physical aperture of the optical system. Typically, the exit aperture is the last element of the eyepiece.

Exit Pupil. The exit pupil is the image of the aperture stop formed by the optical elements between the aperture stop and the image.

Exit Window. The exit window is last optical element of the optical system intersected by a ray originating from a distant object.

Eyepiece. The eyepiece, also called the ocular, is a lens system located between the final real image in an optical system and the observer's eye.

Eye Relief. The eye relief is the distance between the vertex of the last optical element of an optical system and the plane of the exit pupil.

f-number (f#, F or f_{no}). f-number is the ratio of the effective focal length of an optical system to the diameter of its entrance pupil. The f-number is also known as the aperture ratio.

Field Stop. An aperture located at or near an image plane of an optical system that determines the size and format of the image. The field stop limits the size or angular subtense of the object that can be imaged by the system and also determines the field of view.

Field-of-View (FoV). The limits of the field or area displayed by, or viewed through, an optical/electro-optical system. The field-of-view is usually expressed in angular terms.

Figure of Merit. Figure of merit is any parameter that is used to define the performance of a system against a standard metric. A figure of merit is typically defined to highlight (i.e. weight) or combine specific performance parameters into a single evaluation parameter. Figures of merit can be highly subjective and/or biased by the manner in which they are defined and must be used with caution.

Fourier Transform. The Fourier transform of a function f(x) is defined as:

$$F(s) = FT\{f(x)\} \equiv \int f(x) e^{-i2\pi xs} dx$$

where s is the spatial frequency.

Image Space (IS). Image space is the region in which the image, formed by radiation which has passed through an optical system, exists.

Integrated Visible Photopic Transmission (IVPT). The IVPT is defined as the transmission of an optical component or system, weighted with respect to the wavelength response of the human eye at high ambient brightness (i.e. the photopic curve) and defined by the following equation:

$$\tau_{IVPT} = \frac{\int_{\lambda 1}^{\lambda 2} \Phi_t(\lambda) k_P(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda 2} \Phi_{in}(\lambda) k_P(\lambda) d\lambda}$$

where: Φ_t is the radiant flux (power) transmitted through the test item,

Φ_{in} is the radiant flux (power) input to the test item,

$k_p (\lambda)$ is the normalized photopic response as shown in Figure A-3(a),

λ_1 is the lower wavelength of the photopic response curve,

λ_2 is the upper wavelength of the photopic response curve.

The numerator is the measured illumination through the test item, weighted by the photopic curve. The denominator is the measured illumination input to the test item, weighted by the photopic curve; i.e. the reference spectrum.

Integrated Visible Scotopic Transmission (IVST). The IVST is defined as the transmission of an optical component or system weighted with respect to the wavelength response of the human eye at low ambient illuminance (i.e. the scotopic curve). The form of the equation for IVST is the same as that shown in the definition for IVPT.

Isoplanatism. The characteristic of a region of object space such that the point spread functions of nearby object points are approximately equal.

Line Spread Function. Line spread function is a mathematical representation of the spatial distribution of intensity in the image plane of a line source, in a direction perpendicular to the axis of the source.

Luminance. Luminous flux emitted from a surface per unit solid angle per unit of area projected onto a plane normal to the direction of propagation.

Magnification (Angular). Given an object centered on the optical axis that subtends an angle ω in object space and ω' in image space, the angular magnification of the system is:

$$M(\omega) = \frac{\tan(\omega')}{\tan(\omega)}$$

where ω and ω' are expressed in radians. For small angles, this expression may be approximated by ω'/ω.

Marginal Ray. A marginal ray is a ray from an on-axis object point that just passes the edge (margin) of the entrance pupil.

Modulation. In general, the system induced change in the properties of an input wave train as seen in the output wave train, (e.g. amplitude, frequency and phase). In optics, modulation is used as a synonym for contrast, especially when applied to a bar target imaged by an optical system.

Modulation Transfer Factor. For a bar pattern target whose luminance varies sinusoidally, the property of an optical system expressed as the ratio of the image contrast to the object contrast at a given spatial frequency.

Modulation Transfer Function (MTF). The MTF is the modulus of the OTF (see definition of OTF). It provides a measure of an optical system's ability to transfer the contrast (modulation) of an object to its image. MTF may be expressed graphically and is effectively a plot of normalized modulation transfer factor against object space spatial frequency.

Numerical Aperture (NA). The sine of the vertex half angle of the largest cone of marginal rays that can enter an optical system or element multiplied by the index of refraction of the medium in which the vertex of the cone is located.

Nyquist Criterion. In image acquisition, the sampling frequency must be at least twice the highest spatial frequency component in the image data being sampled.

Nyquist Frequency. Nyguist frequency is the highest spatial frequency that a sampled system can accurately reproduce, in accordance with the Nyquist criterion. This is given by $F_N = 1/2\alpha$, where α is the detector angular subtense (mr) and F_N is the Nyquist frequency (cy/mr).

Object Space (OS). Object space is the region from which radiation enters the entrance pupil of an optical system and in which the object resides.

Objective. The objective of an optical system is the element, or combination of elements, which receives light from the object and forms the first or primary image.

Optical Axis. Optical axis is the line passing through both centers of curvature of the optical surfaces of a single lens. For a multiple lens system the optical axis is the line passing through the geometrical center of the individual optical elements. For a telescopic system the optical axis is the line that defines the center of the field of view. Optical axis is sometimes referred to the optical reference line (ORL).

Optical System. An optical system is a group of refractive, reflective and/or diffractive components designed to perform a specific optical function.

Optical Transfer Function (OTF). The OTF is a functional relationship describing an optical system's ability to transmit the spatial frequency components of an object to its image. The OTF is a complex function comprising modulation (real) and phase (imaginary) transfer functions. The respective parts are known as MTF and PTF, and are defined by:

$$OTF(s) = MTF(s)e^{-iPTF(s)}$$

where s is the spatial frequency in cycles/milliradian (cy/mr) or an equivalent measure.

Panoramic Sight. A panoramic sight is usually constructed in a periscopic format and is hard mounted to its host vehicle. It is typically used where panoramic telescopic vision is required from a fixed observation position within the host vehicle, e.g. from the commander's position in a main battle tank or from within the cockpit of an attack helicopter. The optical train incorporates derotation optics so that when the sight head containing the periscope mirror is rotated about the sight body in a horizontal plane, the image retains its orientation relative to the observer.

Parallax. Parallax is the optical phenomenon that causes the apparent change in relative position between two objects when the location of the eye is displaced laterally. Parallax is observed in a telescope when the reticle is not located in an image plane or the image is observed along a line of sight that is not coincident with the optical axis of the system.

Paraxial Ray. A paraxial ray lies close to and almost parallel to the optical axis and obeys first order, also called Gaussian, optics such that the ray's angle with the optical axis, μ (in radians), can be used in place of $\sin(\mu)$ or $\tan(\mu)$, in accordance with the small angle approximation.

Periscope. A periscope is an optical instrument that displaces the line of sight, or optical axis, parallel to itself. Displacement can be in any direction, depending on orientation of the periscope axis.

Phase Transfer Function (PTF). The PTF is the argument of the OTF (see definition of OTF). It is the functional relationship describing the relative phase shifts of the spatial frequency components of an image relative to its object. A phase shift of 180 degrees corresponds to a contrast reversal.

Photopic Filter. A photopic filter has a transmission curve that, when combined with the spectral output of a broad band light source (such as a tungsten halogen lamp) and the spectral responsivity of a photodetector, produces an overall system spectral characteristic that simulates the photopic (daylight) response of the human eye. The spectral response of the human eye for high and low illuminance conditions is shown graphically in Figure A-3 and numerically in Table 1.

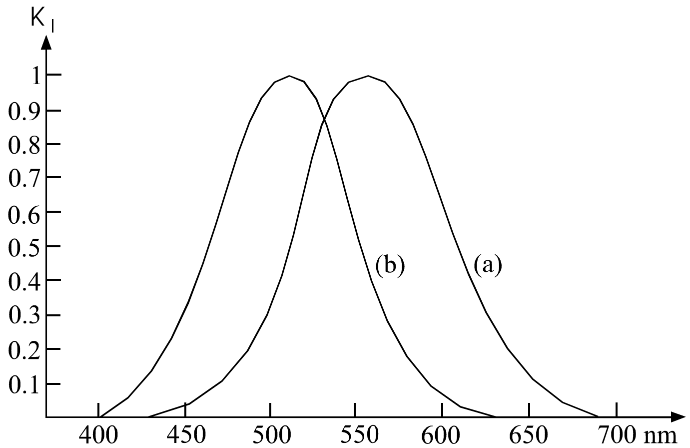

Figure A-3. The Normalised Visibility Curve, K_λ, of the Average Human Eye for (a) Photopic (High Illuminance) and (b) Scotopic (Low Illuminance) conditions

Table A-1. Photopic/Scotopic Eye Response Data (Normalised).

λ (nm)	Photopic Response	Scotopic Response	λ (nm)	Photopic Response	Scotopic Response
380	0.00004	0.000589	590	0.757	0.0655
390	0.00012	0.002209	600	0.631	0.03315
400	0.0004	0.00929	610	0.503	0.01593
410	0.0012	0.03484	620	0.381	0.00737
420	0.004	0.0966	630	0.265	0.003335
430	0.0116	0.1998	640	0.175	0.001497
440	0.023	0.3281	650	0.107	0.000677
450	0.038	0.455	660	0.061	0.0003129
460	0.060	0.567	670	0.032	0.0001480
470	0.091	0.676	680	0.017	0.0000715
480	0.139	0.793	690	0.0082	0.00003533
490	0.208	0.904	700	0.0041	0.00001780
500	0.323	0.982	710	0.0021	0.00000914
510	0.503	0.997	720	0.00105	0.00000478
520	0.710	0.935	730	0.00052	0.000002546
530	0.862	0.811	740	0.00025	0.000001379
540	0.954	0.650	750	0.00012	0.000000760
550	0.995	0.481	760	0.00006	0.000000425
560	0.995	0.3288	770	0.00003	0.000000241
570	0.952	0.2076	780	0.000015	0.000000139
580	0.870	0.1212			

Point Spread Function. Point spread function is a mathematical representation of the spatial distribution of intensity in the image plane of a point source.

Principal or Chief Ray. A principal or chief ray is a ray from the furthest off-axis object point that passes through the center of the aperture stop. The principal ray enters the optical system passing through the center of the entrance pupil and exits the system passing through the center of the exit pupil. It is the effective axis of an oblique beam.

Principal Plane. The intersection of the projections of the incoming (forward projection) and exiting (backward projection) paraxial rays. The plane is the locus of the intersection of all the rays passing through an optical system. At any finite distance from the optical axis, the principal plane will approximate to a spherical surface.

Principal Point. The intersection of the principal plane with the optical axis.

Pupil. A pupil is an image of the aperture stop, (see also, entrance and exit pupil).

Radial OTF. The OTF at an off-axis point for a spatial pattern whose spatial frequency components are along the radius (object bars oriented perpendicular to the radius).

Rayleigh Quarter-Wave Criterion. Rayleigh quarter-wave criterion is a criterion of the image quality produced by an optical system. If the optical path difference does not vary by more than one quarter of a wavelength of light over the aperture of an optical system, the image quality as perceived by an observer will be perfect. Under these conditions, the wavefront at the exit pupil has to be contained between two spherical surfaces whose radii, when centered on the same image point, differ by no more than one quarter of a specified wavelength, e.g. 550nm.

Rayleigh Resolution Criterion. For a circular diffraction limited (i.e. aberration free) lens with a focal length, f, and aperture, D, as shown in Figure A-4, the images of two points are just resolved when they are separated such that the center of the Airy diffraction pattern of one point falls on the first minimum of the Airy diffraction pattern of the other.

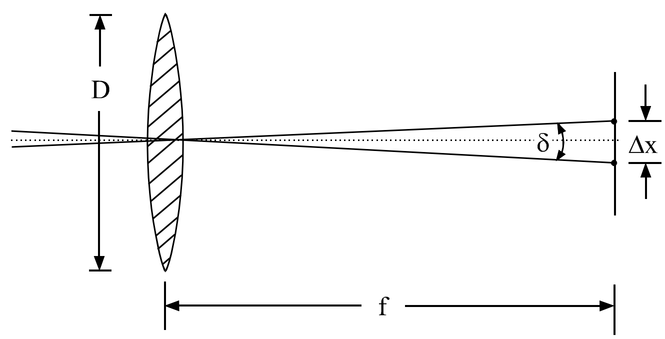

Figure A-4. Relation between the Aperture, D, the Effective Focal Length, f, and the Image Separation, Δx, of Two Just Resolved Point Objects.

This resolution condition exists when the angular separation of the images of two object points is:

$$\delta[\mu rad] = \frac{1.22\lambda[nm]}{D[mm]} = \frac{\Delta x[\mu m]}{f\,[nm]}$$

The corresponding spatial frequency, is:

$$\omega_{co}\left[\frac{cy}{mr}\right] = \frac{1000.0\,D[mm]}{1.22\lambda[nm]} \approx \frac{819.7D[mm]}{\lambda[nm]}$$

and in the image plane is:

$$\omega_{co}\left[\frac{lp}{mm}\right] = \frac{1000000}{1.22\lambda[nm]\dfrac{f\,[mm]}{D[mm]}} = \frac{819700}{\lambda[nm]\,f_{no}}$$

where λ is the measurement wavelength and f_{no} is the f-number.

Reference Plane. The plane, perpendicular to the optical axis of the measurement system, to which all points on the axis may be referred in terms of mechanical position. A reference plane will typically be co-incident with a mechanical feature of a measurement system, such as a lens mount, the plano surface of an optical element or the surface of a supporting fixture.

Resolution. The resolution or resolving power, of an optical system is a measure of the system's ability to distinguish closely spaced objects. Resolution is usually expressed as the angle subtended by 1 cycle of the highest spatial frequency of a standard bar target that can just be discriminated when the target is in object space. The units of resolution are typically arc seconds or cycles/milliradian (cy/mr) in object space or cycles/millimeter (cy/mm) in the image plane.

Reticle. An optical element located at, or projected into, an image plane of an optical instrument that consists of a pattern (e.g. crosshair, linear or angular graduations) to assist the observer when pointing the instrument or measuring target characteristics.

Sampling Theorem. A mathematical theorem stating that detector array image sampling frequencies must be at least twice the highest frequency contained in the image in order to accurately resolve the image.

Scotopic Filter. A scotopic filter has a transmission curve that, when combined with the spectral output of a broad band light source (such as a tungsten halogen lamp) and the spectral responsivity of a photodetector, produces an overall system spectral characteristic that simulates the scotopic (dark adapted) response of the human eye. The spectral response of the human eye for high and low illuminance conditions is shown graphically in Figure A-3 and numerically in

Table 1.

Shift Variance. An optical system that exhibits shift variance departs from the condition for which a shift in the position of the input causes a corresponding shift in the position of the output without a change in image quality. Note that a system which is shift invariant is isoplanatic.

Sinc Function. The mathematical function, denoted sinc(x), is defined as:

$$\mathrm{sinc}(x) = \frac{\sin(\pi x)}{\pi x}$$

Spatial Frequency (fundamental, three-bar). Spatial frequency is the reciprocal of the line spacing of a repetitive object such as a series of equally spaced lines or bars. Figure A-5 shows a three-bar target with one bar width and one bar-to-bar spacing equal to b. A 5:1 aspect ratio ensures that when using an optical or electro-optical sensor to view a three-bar target, one axis of resolution in the image does not influence the other, i.e. crosstalk. One dark bar and one light bar (spacing) constitute one cycle (cy). The spatial frequency is expressed in cycles/millimeter (cy/mm), i.e. 1/2b, in an object or image plane or as cycles/milliradian (cy/mr) when viewing a distant object. Note: The spatial frequencies (s) generated by a single slit of width w can be represented by a sinc function, sin(πsw)/πsw, which theoretically has infinite angular spatial frequency content.

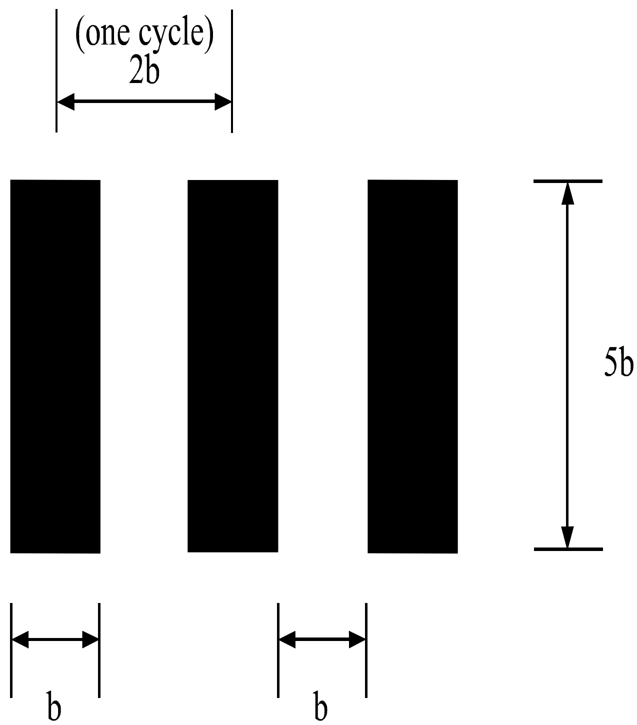

Figure A-5. A Three Bar Target.

Spectral Transmission. The spectral transmission $\tau(\lambda)$, of an optical system is defined as the ratio of the light, at wavelength λ, transmitted through the system to the light incident on the system. This is given by: $\tau(\lambda) = \Phi_t(\lambda)/\Phi_{in}(\lambda)$, where Φ_t is the spectral flux transmitted through the test item at wavelength λ and Φ_{in} is the spectral flux input to the test item at wavelength λ.

Stop. A stop is a physical aperture or diaphragm in an optical system that limits the diameter of the bundle of rays passing through the system.

Strehl Intensity Ratio. The ratio of the central (peak) intensity of the aberrated point spread function produced by an optical system to the central intensity of the point spread function produced by the same optical system if it had a performance limited only by the effects of diffraction. An optical system that exhibits a Strehl ratio of 0.8 has a perceived image quality that conforms to the Rayleigh quarter wave criterion.

T-number. T-number is the equivalent f-number (F) of a fictitious lens having a circular aperture and 100% transmission that would give the same central illumination as the test lens. The T-number is calculated by:

$$\mathrm{T-number} = \frac{\mathrm{EFL}}{2}\sqrt{\frac{\pi}{A\tau}}$$

where EFL is the effective focal length, A is the area of the entrance pupil of the test item and τ is the average transmission of the lens system. For a circular and unobstructed system, the T-number is:

$$\mathrm{T-number} = \frac{F}{\sqrt{\tau}}$$

Tangential OTF. The OTF at an off-axis point for a spatial pattern whose spatial frequency components are perpendicular to the radius (object bars oriented along the radius).

Telecentric System. A telecentric system is one in which the center of the aperture stop is at a principal focus. If the entrance pupil is at infinity, the system is said to be telecentric on the object side. If the exit pupil is at infinity, the system is said to be telecentric on the image side.

Telescope. A telescope is an arrangement of lenses or lenses and mirrors that produces a magnified retinal image of a distant object. For small angles, the ratio of the angular subtense of the image as viewed through the telescope to the angular subtense of the object viewed with the naked eye from the same position is the angular magnification of the telescope (see also definition 1.3.48).

Telescope (Afocal Condition). The optical condition of a telescope corresponding to a zero diopter setting of its eyepiece. In this condition, the front and back focal lengths of the telescope are infinite and the image observed through the telescope is at infinity. In practice, a telescope eyepiece is typically adjusted to a negative diopter setting to produce an image at a finite distance for relaxed viewing.

Tilt. Tilt is any angular deviation between the optical axis of an optical system and the axis of an element in the system.

Test Accuracy Ratio (TAR). The maximum permitted error of the unit to be measured or calibrated divided by the known error of the measuring or generating device used to perform the measurement. For example, if it is required that a system or equipment output parameter be accurate to 8% (maximum permitted error) and a known accuracy (maximum known error) of the measuring device used to measure the output parameter is 2%, then the TAR is 4.

Uncertainty Analysis. Uncertainty Analysis is the analysis and evaluation of all sources of error that contribute to the overall measurement error of a system property. These include, but are not limited to, the effects of the environment, the measuring equipment, the test item itself, and the operator. Particular care must be taken to discriminate between sources of error that give a random distribution about the true value and those which introduce a systematic bias to the results.

Vignetting. Vignetting is the loss of image illuminance within an optical system as a function of increasing off-axis angle. An example is image forming pencils at large angles in a camera, where the edge of the lens obstructs some of the rays. However, any object that obstructs image forming rays can cause this effect.

Visual Acuity. Visual acuity is a quantitative measure of an observer's ability to perceive fine detail. The average value for a healthy eye is one minute of arc, or 6.7lp/mm, at the normal viewing distance of 250mm. Visual acuity is usually expressed as the Snellen fraction, e.g. 6/3, when using a letter type test chart. The numerator in this fraction represents the distance from the observer to the test chart (typically 6 meters) and the denominator the distance at which the gaps in the matrix of the smallest legible letter subtend one minute of arc. Note that visual acuity can also be expressed as the reciprocal of the eye's resolution (in minutes of arc).

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