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# OPTICAL TOLERANCES FOR ALIGNMENT AND IMAGE DIFFERENCES FOR BINOCULAR HELMET-MOUNTED DISPLAYS

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Reviews the literature on optical alignment and image difference tolerances for binocular devices. Tolerances for vertical and horizontal misalignment and for rotation, magnification and luminance differences are recommended. Recommendations are made for collimation tolerance and for eye relief and exit pupil diameter for helmet-mounted binocular displays. Formulas are derived for magnification difference tolerances for partially and totally overlapping fields of view.

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# PREFACE

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# Optical Tolerances for Alignment and Image Differences for Binocular Helmet-Mounted Displays

## PURPOSE

This document has three objectives: (1) to apply the findings of research in optics and vision as well as current optical practice to the specification of optical tolerances for binocular helmet-mounted displays (HMDs), (2) to serve as an introduction to, and tutorial on, optical tolerance limits for image differences and optical alignment of binocular HMDs, and (3) to formulate a set of optical tolerance limit specifications useful for specifying, purchasing, inspecting, testing, and adjusting binocular HMDs.

For several years the Human Engineering Division of AAMRL at Wright-Patterson Air Force Base, Ohio has been the Air Force center for the development of head-up helmet-mounted displays (HMD). Recently, the Division has been developing the technology for binocular HMDs, and has the first such device, one fabricated for research purposes. Essential to the development and application of such binocular devices is the generation of specifications for the optical characteristics required for human use by members of the Armed Forces in real missions.

Since binocular HMDs represent a brand new technology, required optical characteristics have not been documented. The author, therefore, examined the scientific and technical literature for human factors data relevant to the alignment and adjustment of binocular helmet-mounted HUDs. Other staff members are researching required luminance and color characteristics.

The present document reviews relevant literature, discusses tolerances and adjustments in a tutorial manner and presents tentative recommendations for adjustments and tolerances.

## INTRODUCTION

In a binocular helmet-mounted display (HMD) there are two images, one for each eye. The two images may differ in several ways, and both horizontal and vertical alignment error may be present at the same time. Alignment errors refer to lack of parallelism of the two optical axes. Table 1 lists and defines types of alignment errors and optical image differences.

Zero optical image differences and zero alignment errors are not possible with binocular devices. A very close approach to perfection is quite expensive in dollars and in equipment weight and volume. Fortunately, near perfection is not necessary: some imperfection can be present without ill effects.

With a well-adjusted binocular device, such as a binocular HMD, an observer fuses the two images into one so rapidly that he never notices that

Table 1

Definitions of Alignment Errors and Optical Image Differences

| Fault or Error | Definition |
|---|---|
| Vertical Misalignment | One optical axis is tilted up or down with respect to the other axis. Difference in vertical position of images. |
| Horizontal Misalignment | One optical axis points inward or outward. |
| Rotation Difference | One image is rotated (tilted sideways or twisted). |
| Magnification Difference | Objects in one image are larger than in the other. |
| Luminous Difference | One image is less luminous (dimmer) than the other. |
| Contrast Difference | The two images differ in contrast. |
| Collimation Difference | The optical distances to the images differ. |
| Collimation Error | Optical images not at optical infinity. |

he is viewing two images: He sees and is aware of only one image. This fusion involves both neural and eye muscle effort, but the effort is both unconscious and rapid. When alignment errors and image differences worsen, fusion is still rapid, but eyestrain may become apparent. As conditions worsen further, fusion becomes more difficult and finally is not possible: two separate images are seen. Seeing a double image of a single object is called diplopia. Noticeable eyestrain usually occurs at appreciably smaller tolerance limits than are required to produce double vision.

There is a time or use effect: effort to maintain fusion has a cumulative effect. Equipment that appears to be entirely adequate, having no noticeable ill effects, when used for a short time, may prove to be unacceptable, or even intolerable, when used for long time periods. Eyestrain and visual fatigue may become quite noticeable, and headache may occur. A headache, even a severe one, may develop even when no eyestrain or visual fatigue is apparent. The observer may not know why he has a headache, and is unlikely to attribute it to optical misalignment..

In addition to an accumulative effect, there is a wide range of individual differences in tolerances. Some observers can tolerate, with no obvious ill effects, much larger misalignment than can others. Indeed, a degree of alignment error unnoticed by, or even undetectable by, one observer may be unacceptable to another.

Zero optical alignment tolerances and zero tolerances for image differences are not practical: they would be difficult and expensive to obtain and could not be retained in use. Practical tolerances permit almost all observers to function, over extended use intervals, with negligible loss in visual capabilities and without eyestrain, visual fatigue, or development of a headache. Because of the large individual differences in observer tolerance to misalignment and image differences, and because ill effects are not always immediately apparent, a quick visual inspection is not adequate for determining if alignment errors and image differences are within an acceptable range. This means that Optical Tolerance Limits, usually called tolerances, must be specified with numbers and individual instrument errors and image differences must be measured to be sure that every HMD is within all tolerance limits.

As previously noted, overly strict or stringent tolerance specifications cause equipment to be overly expensive, yet not detectably better, in either comfort or capability, than devices with somewhat larger tolerance limits. At the other extreme, overly loose or liberal tolerances result in equipment that is unsatisfactory for some users and unusable by some. Practical specifications are, and must be, a compromise. One level of compromise that is widely used in equipment procurement is to set tolerances so that 95 percent of all users are accommodated with little or no loss in comfort or capability. Unfortunately, research data is not available to permit such tolerance specifications for HMD optics. There are some data sources, but usually not enough people were used as test observers to establish tolerance limits that will include any given percentage of HMD users.

Binocular instruments, such as binoculars, field glasses, binocular telescopes, and binocular microscopes have been used for scores of years. Experience accumulated with these instruments, together with some limited scientific research, has resulted in what might be called current optical practice. Some of the tolerances used in current practice have unknown origins. Some is based on what, at some time or other, was judged as being sensible and reasonable.

## LITERATURE SURVEY

Jacobs (1943) discusses the optics of misalignment in binoculars . His tolerance formulas give the maximum amount of permissible misalignment as a function of optical magnification. The formulas indicate that the eyes should not have to diverge by more than 7.5 arc minutes, converge by more than 22.5 minutes, or have to tolerate over 8 minutes of vertical misalignment. He does not say where he obtains his numerical values, although he lists some pre-1932 references at the end of the chapter on binoculars and battery-commander telescopes (a form of telebinocular).

During World War II the University of Texas reviewed, for the Office of Naval Research, literature that could be related to the design specifications of hand-held binoculars to be used visually. Using this literature review, in June of 1946 the Army-Navy-National Research Council recommended that vertical misalignment of binoculars should not exceed 14 arc minutes, observers should not have to converge their eyes more than 28 minutes of arc or diverge them more than 14 minutes. How the vision committee arrived at the numerical values that they recommended is not reported. They do say, however, that the recommendations are not founded upon a firm basis and they recommend that psychophysical experimentation should be done. The committee recommendations on alignment is one of the unauthored papers reported by Harvey (1970, particularly page 312).

Ingalls and Pestrecov (1948) discuss, for engineers and scientists, the centering or alignment of optical systems. Their concern is with aligning the optical elements in one optical path, rather than with the alignment of two optical paths, and they give no values for tolerances. They are mentioned because, as a classic on alignment, their article is often quoted by other authors in discussion of binocular instruments.

Johnson (1960) says that observers differ in tolerance to alignment error, but that "the results of a large number of tests seem to indicate that, for a normal person, the safe limit to impose on the induced angle of accommodation is $2^{\circ}$ 18' (4 prism diopters) horizontal convergence, $1^{\circ}$ 9' (2 prism diopters) horizontal divergence and 34.5' (1 prism diopter) of vertical vergence". He gives no references or supporting data.

MIL-Handbook-141 (1962), the military standardization handbook on optical design, on page 17 of section 4, says that a difference in magnification in the two sides of a binocular instrument causes an apparent distortion of space. It says that a difference in magnification of 1 or 2 percent or more usually results in visual strain and discomfort and that differences of 5% usually preclude binocular vision. Some people, it states, cannot tolerate more than .5%, while others may tolerate a little more than 2%. It recommends that magnification differences should not exceed 2%. Further, the amount of light to the two eyes should differ by less than 10%, while vertical misalignment should not exceed .5 prism diopter (17 arc minutes), and a maximum value of .33 diopter (11 arc minutes) difference may be desirable. Any twist (or rotation difference) should be kept to a minimum. No references are given for any of the recommended tolerances.

The U.S. Navy training course textbook, "Optical man 3 & 2" (1966) has a section (page 470) on tolerance and performance requirements for U.S. Navy binoculars. In this section it says that the optical axes of the two barrels must be parallel within 2 arc minutes vertically, within 4 minutes divergence, and within 2 minutes convergence. It says that failure of the axes to stay within these tolerances causes eyestrain. Interpupillary distance scale readings must be accurate within 1 millimeter to prevent eyestrain. To avoid a blurred image and eyestrain, the two diopter (or focus) scales for the eyepieces must be accurate within 1/4 diopter. The light transmission of the two barrels may not differ by more than 3 percent. No references or supporting data are given.

Gold and Hyman (1970) experimentally determined visual requirements for head-up displays. They investigated both exit pupil size and binocular misalignment. To examine misalignment, they developed a laboratory telecentric optical viewing system. Subjects viewed dynamic images through the optics against a static view of a real-world background. The background was an aerial view of real terrain, including a few buildings. Viewing times were 15 seconds, which they said were adequate for indicating comfort in real flight. In each 15 second presentation, observers judged visual comfort level on a scale ranging from 1 (excellent) to 6 (image doubling more than 50% of the time). Three observers were used.

They found that when a real-world background was used, as compared to a homogeneous background, the maximum permissible angular misalignments were much smaller, by as much as a factor of 10. Their criteria of adequate visual comfort for sustained viewing requires much smaller angular misalignments than those at which image doubling (diplopia) occurs. They found that vertical misalignment should not exceed 1 milliradian (3.4 minutes of arc), and that, also, the eyes should not have to tolerate more than 1 milliradian of divergence. Comfort in extended viewing, in addition, requires that horizontal convergence should not exceed 2.5 milliradians (8.6 minutes of arc).

Gold (1971) did a second study to obtain alignment tolerances for head-up displays (HUDs). He used an optical system that provided symbols from a CRT superimposed on terrain imagery provided, via a beamsplitter, by 16 mm motion picture imagery collected at low altitude. He thus simulated viewing symbols through a HUD with a dynamic (moving) real-world background. The field of view was quite narrow: 12.5 degrees for both eyes with a 6 degree overlap. Each test run was followed by observers rating the run on a 6-point visual comfort scale. Data is reported for 4 observers. Disparities much smaller than those that produce image doubling (diplopia) caused complaints of visual stress and annoyance. Test condition differences were smaller than test result differences between observers. Individual observers differed by a large and statistically significant amount in misalignment tolerances. In terms of allowable angular misalignment, tolerances were much smaller (smaller angles) when disparities were viewed against a real-world background than when viewed against a homogeneous background. From examination of his data, Gold concluded that vertical misalignment should not exceed 1 milliradian (3.4 arc minutes), convergence should not exceed 2.5 mr (8.6 minutes), and divergence should not exceed 1 mr (3.4 minutes). His results with a dynamic background were essentially the same as those obtained by Gold and Hyman (1970) when static real-world backgrounds were used.

Gibson (1980) performed three experiments with head-up displays in which both an outside world scene and symbols (a winged aircraft and horizontal bars) were viewed. The head-up display was not helmet-mounted.

Negative disparity between world scene and symbols was slowly increased until the onset of visual discomfort or unease. The mean negative disparity for unease or discomfort was .83 mrad, i.e., when the HUD symbology was .83 mrad behind the target. The range for 10 subjects was +.10 to -1.06 mrad. To find at what distance the symbology should be projected, a second experiment with a simulated weapon-aiming situation was simulated. The same 10 subjects adjusted the display for optimum viewing of both the aiming circle and the target in the outside world. The mean setting was +.72 mrad, so that the optimum viewing position was a positive disparity of .38 mrad, i.e., aiming circle between the observer and the target. Nine of 10 subjects set the display to a positive disparity. A third experiment was done to determine the point at which subjects could perceive a parallax between the HUD imagery and the outside world. The mean threshold for the 8 subjects used was .23 mrad. The results of Gibson's study is that when symbols appear in a head-up display, negative disparity (symbols behind the scene) should not be present, and that the optimum viewing position of symbology is in front of the scene with a positive disparity of .38 mrad.

MIL-Standard-1472C (1981), "Military Standard on Human Engineering Design Criteria for Military Systems, Equipment, and Facilities", has a section (page 211) on binoculars and biocular. It says: "binocular/biocular instruments should have an eyepiece separation scaled from 50 to 73 millimeters with one millimeter interval markings ..." "magnification differences of the two barrels should not exceed 2% ..." "luminous transmission differences in the two barrels should not exceed 5%". No supporting data or references are given, and no alignment tolerances are specified.

Binocular head-up displays (HUDs) may be used by observers in vehicles whose windscreens or canopies produce optical disparities. For example, they may be used in an aircraft whose thick curved windscreen causes light rays from a distant point in the environment to be bent or deviated by different amounts for the two eyes of the observer. It has been found that, with some aircraft windscreens, light rays from a distant point in the environment appear to come from a point as near as 40 feet away from the observer. When collimated images from a sensor are presented to an observer by a binocular HUD, the directly-viewed environment seen through such a windscreen and the HUD-presented image will not appear to be at the same distance. When the distance between them is appreciable, looking at either one of them produces double images (diplopia) of the other one.

Because of Air Force pilot complaints of double vision with a wide-field-of-view HUD, Genco (1983) measured diplopia thresholds. He used 32 non-pilot volunteers whose vision was measured and found to meet at least Flying Class 2 Vision standards. Observers fixated a distant object, a lamp post, and reported whether or not a briefly-presented distant luminous line appeared single or double. They also reported if a single line appeared, but was misaligned with the target, which would indicate suppression of vision in one eye. Four thresholds were determined by a bracketing technique for each observer: one at each crossing of two disparity directions (positive and negative) with two exposure times for each (.1

second and 3 seconds). It was found that: (1) observers were relatively intolerant of negative disparity, (2) very short glances were less likely than longer viewing to produce double vison, (3) individuals varied considerably in resistance to double vision, and (4) a large portion of responses involved suppression of vision from one eye. Because the distributions of threshold values were strongly skewed, rather than symmetrical, median scores, rather than means, were reported. Medians are values above and below which half of the scores fall. The overall median negative disparity threshold for double vision was 1.2 milliradian (4.1 arc minutes), and the overall positive threshold was 2.6 mrad (8.8 arc minutes). Thus, half of the observers had vision problems at those disparity values. Genco recommended 4.1 arc minutes of eye divergence and 8.8 arc minutes of eye convergence as the maximum misalignments acceptable for wide FOV head-up display systems combined with cockpit canopies. It is of some interest that Genco's recommendations for convergence and divergence tolerances are essentially the same as those of Gold and Hyman (1970) and Gold (1971) who limited convergence to 8.6 arc minutes and divergence to 3.4 arc minutes.

## COMMENTS ON LITERATURE SURVEY AND DISCUSSION

A search of the technical literature for tolerances for satisfactory human use of binocular devices revealed that frequently, indeed usually, no research data, or any other supporting data, was cited. For example, the recommendations given in Military Standard 1472C (1981) and in Military Handbook 141 (1962) are presented without references or supporting data. Even optics textbooks usually present recommended tolerances without supporting them.

Since binocular helmet-mounted displays are a brand new technology, no data on tolerances derived from their use or from tests done with them has been collected. However, they are a form of head-up display (HUD), and HUDs have been around for some time, particularly for cockpit use in aircraft as discussed earlier. Gold (1971) and Gold and Hyman (1970) conducted research to obtain alignment tolerance data for HUDs. However, Gold's data is from only 4 satisfactory subjects, hardly representative of any population. Gold and Hyman (1970) used only 3 observers. Both studies obtained essentially the same results.

Examination of the technical literature, in addition to revealing the small number of tested observers used in almost all relevant research, also revealed large differences in the tolerance limits cited by the different authors. A large part of the difference between authors is undoubtedly due to their use of different criteria for deciding what is tolerable. For example, visual comfort criteria of acceptability yield much smaller (tighter) tolerances than do image fusion criteria, i.e., avoidance of double vision. Gold (1971) noted that observers complained of visual stress and annoyance caused by amounts of misalignment that were considerably smaller than those that produce image doubling. A second reason for author differences is their sampling of different populations of observers. Related to this is the very large differences in tolerances of individual observers. With only a few observers, this large observer difference is likely to yield a nonrepresentative sample of observers. Nonrepresentative samples from different populations would not be expected to yield very similar test results.

Finally, and possibly of most importance, investigators who used complex scenes, such as real world pictures, obtain results that can differ by a large amount from results obtained with uniform backgrounds or with few image details. Results can differ by as much as a factor of ten. Gold and Hyman (1970) and Gold (1971) note that disparity tolerances were significantly lower (tighter) when images were viewed against a simulated real-world background, compared to a homogeneous visual background. Thus, when a complex background is present, permissible differences between the right and left images were smaller. To avoid confusion it appears that use of the terms "tighter" or "more stringent" would be preferable, in a tolerance context, to use of "increase". Also, "looser" or "less stringent" may be preferable to "larger".

The rather large differences in recommendations for tolerance limits cited in the literature are apparent from an examination of the data in Table 2. In view of the preceding paragraph, the large differences are not surprising. The optical tolerance limits that are recommended in the present paper are given in a later section.

It is apparent that some of the tolerance values in Table 2 are given to 3 significant digits, implying an accuracy of better than 1%. These multi-digit values were sometimes obtained by converting from one or two digit values originally in different measurement units. An example is prism diopters converted to arc minutes. For example No. 4, Johnson, lists 34.5 arc minutes tolerance for vertical misalignment tolerance, a value obtained from 1 prism diopter that he recommends, or $2^{o}$ 18' for convergence, which is 4 prism diopters. Johnson did note that his recommendations were in prism diopters and arc minutes. The point is made because much of the published data was collected using standard optometry equipment with 1/4 diopter measurement steps. Original test data, then, often has a measurement accuracy no better than about 10%, and is sometimes worse. The fact that measurement intervals may be large, plus the subjective nature of the measurements and the very large differences in tolerances between different observers indicate that is it misleading to cite tolerances beyond two digits.

A second interesting thing about the data in Table 2 is the rather small values for convergence tolerances of the eyes. Tolerances are quite small relative to how much nearly everyone can converge his eyes. Human eyes easily converge by an angle exceeding $16^{o}$. However, convergence in which the visual axis of the eyes do not intersect at even approximately the optical distance to the image involves noncorresponding retinal points and will result in considerable effort to fuse the two images on the two retinae. The attempt to fuse images may fail, resulting in double vision, diplopia, at easily-achieved eye convergence angles.

Table 2

Some Tolerance Limits for Binocular Instruments Cited in Technical Literature

| No. | Author/Source | Vertical Misalignment | Convergence | Divergence |
|---|---|---|---|---|
| 1 | MIL-STD 1472C (1981) | Not Given | Not Given | Not Given |
| 2 | Farrell & Booth (1984) | 10' | 2.7° | 0 |
| 3 | Jacobs (1943) | 8' | 22.5' | 7.5' |
| 4 | Johnson (1948) | 1 P.D.*=34.5' | 4 P.D.=2° 18' | 2 P.D.=1° 9' |
| 5 | MIL-HDBK-141 (1962) | ½ P.D. = 17' | | |
| 6 | Gold and Hyman (1970) | 1 M.R.=3.4' | 2.5 M.R.=8.5' | 1 M.R.=3.4' |
| 7 | Gold | 1 M.R.**=3.4' | 2.5 M.R.=8.6' | 1 M.R.=3.4' |
| 8 | NRC Vision Committee (1946) | 14' | 28' | 14' |
| 9 | Genco (1983) | Diplopia Medians: | 8.8' | 4.1' |

Luminance Difference: No. 2: $<$ 50%, Preferably $<$ 25%, No. 6: $<$ 10%.

Magnification Difference: No. 1: $\leq$ 5%; No. 2: Not producing over 10' vertical misalignment, $\leq$ .8% for 40° FOV; No. 5: $<$ 2%, some can't tolerate more than .5%. J. Enoch (in No. 2):.25 - .5 percent cause visual discomfort.

Rotation Difference: No. 2: Not producing more than 10' of vertical misalignment, not $>$ .5° for a 40° FOV;
No. 4: "... rotation difference can not be tolerated";
No. 6: "keep it to a minimum".

* 1 P.D. = 1 prism diopter = an angle whose tangent is .01 = .573° = .01 radian = 34.5'.

** 1 M.R. = 1 milliradian = .0573° = 3.44 arc minutes = .1 P.D.

Hence, only a small instrument convergence toward the eyes, which is more usually termed divergence (toward object space or the scene), can be allowed. In a study by Farrell et al (1970) cited in Farrell and Booth (1984), it was noted that performance (stereo acuity) decreased when the viewing distance differed from a value that matched the convergence angle by more than .75 diopter. Farrell and Booth (1984) note that, for an average viewer, whose IPD is 63 mm, the .75 diopter tolerance in distance corresponds to a 2.7° tolerance in convergence. However, note in Table 2 the much smaller 8.6 arc minute value for convergence tolerance found by Gold and Hyman and verified later by Gold (1971), both studies using visual comfort of use, rather than stereo acuity, as the criterion of allowable tolerances. As noted earlier, tolerance criteria differences produce large differences in recommended tolerances.

SUMMARY OF DISCUSSION

1. Tolerances are compromises between perfection and practicality. Perfection is unnecessary and even approaching it is too expensive in weight, volume, and dollar cost.

2. Individual observers differ greatly in sensitivity to, and tolerance for, image differences and image alignment errors.

3. Tolerances that will include any given percentage of any particular population are not available for errors in alignment and most types of image differences. The small samples of observers used in most studies do not permit formulation of percentile tolerances.

4. Fusing binocular images requires an effort, and visual fatigue, eyestrain, and headache can result from poorly aligned equipment. Equipment tolerances adequate for brief use may be inadequate for use over long time periods. Problems may not develop for several minutes or even for an hour or more.

5. Image misalignment too severe to permit binocular fusion into one perceived object causes either double vision (diplopia) or suppression of vision in one eye. If suppression occurs, the observer will be unaware of it and will perceive only one image. However, visual capability is less than when both images are fused.

6. Tolerance limits for comfortable use of binocular equipment are much tighter than tolerances based on the ability to fuse images, avoiding diplopia, or tolerances based on stereoscopic acuity.

7. Tolerance limits based upon studies that used real-world or other complex scenes or backgrounds are much tighter (smaller) than those that used simple images or uniform backgrounds. Tolerances for complex backgrounds are tighter by as much as an order of magnitude.

8. Multidigit values, implying high accuracy, cited in the literature are sometimes the result of multiplying 1 or 2 digit obtained-tolerance-values by a conversion factor (e.g. prism diopter conversion to arc minutes) and carrying the answer out to too many digits.

9. Values for tolerances in the literature, particularly in textbooks, often cite no source or other justification and often do not note whether recommendations are based on collected data, experience or common optical practice.

## EFFECT OF FIELD OVERLAP ON TOLERANCES FOR ROTATION AND MAGNIFICATION DIFFERENCES IN THE TWO FIELDS OF VIEW

A large part of the total field of human vision is binocular in that both eyes view the same part of the scene. This part is the overlapping or common part of the total field, and extends to over 60° to either side of center. There is an additional area beyond this common or overlapping area that is seen by only one eye. This is mostly retinal in nature rather than being due to the nose obstructing or cutting off part of the field-of-view for each eye. Spectacle frames cut down the binocular part of the field by a small additional amount, as may any other equipment located close to the face. In the nonoverlapping part of the FOV, since it is viewed by only one eye, there is no binocular vision and alignment tolerances do not apply.

For some tasks a large total head-up FOV is necessary, but it is not necessary that most of this field be binocular, so that the common or overlapping part of the field can be quite small. This is fortunate, for it would require intolerably large and heavy helmet-mounted optics to obtain both a large total FOV and high field overlap.

A decrease in field overlap does not change either vertical or horizontal alignment tolerances in the common or overlap area. A given amount of magnification difference produces the same amount of horizontal image misalignment at the edge of the overlap area, on a line through the field centers, for all amounts of field overlap. However, decreasing field overlap decreases the height of the common overlap area. This means that a given magnification difference produces less maximum vertical misalignment in the common area. In other words, with smaller field overlap, larger magnification differences between the two fields are tolerable. On the other hand, with very small field overlap, a magnification difference may cause horizontal alignment tolerance to be exceeded when vertical misalignment is within tolerance. This is illustrated by an example in Appendix C.

The maximum vertical misalignment produced in the overlap area by a rotation difference does not vary with amount of field overlap. However, since maximum field height in the overlap area is less with ~~more~~ overlap, ~~more~~ rotation difference is required to exceed horizontal alignment tolerance in the overlap area. but, since vertical misalignment tolerance is less (tighter) than horizontal misalignment tolerance, rotation difference tolerance is not changed when amount of field overlap is changed.

Effect of amount of field overlap on alignment tolerances may be summarized by noting that: (1) tolerance for magnification difference is greater (less tight) for smaller field overlap, and (2) tolerance for rotation difference is not changed by variation in percentage of field overlap.

## RECOMMENDED RANGES AND TOLERANCES FOR THE ADJUSTMENT AND ALIGNMENT OF BINOCULAR HELMET-MOUNTED DISPLAYS

The recommendations that follow are based on the literature survey and discussion of preceding portions of the present document. As noted there, considerable ranges of values are to be found in the literature on other binocular instruments. Recommendations are based largely on visual comfort in extended use, and are close to those of Gold and Hyman (1970), Gold (1971), and Genco (1983). The recommendations are the author's, and do not constitute official policy of the U.S. Government.

### 1. IPD Adjustment Range

The IPD adjustment range for a binocular HMD shall be 50 to 73 mm (MIL-STD-1472C) or greater.

Interpupillary distance (IPD) is the distance between the centers of the exit pupils of a binocular instrument, and an observer's IPD is the distance between the centers of the observer's eye pupils.

Measurements made by U.S. Air Force physical anthropologists (Hertzberg et al., 1954) of over 4,000 Air Force flying personnel yielded a mean, or average value, of 63.3 mm for interpupillary distance. Percentile values were: 1st percentile = 55.6, 2nd = 56.3, 5th = 57.7, 95th = 69.6, 98th = 71.0, and 99th = 72.1 mm. The 50-73 mm recommendation of MIL-STD-1472C, then, includes over 99 percent of all U.S. Air Force flying personnel as measured in 1950.

### 2. IPD Adjustment Effects on Alignment

The optical and mechanical axis of the two sides of an HMD shall be close enough in alignment that changes in IPD to adjust it for different users will not cause vertical or horizontal alignment errors or rotation difference to exceed alignment tolerances anywhere in the IPD adjustment range.

With lack of alignment of the optical and mechanical axes, alignment errors will vary with IPD setting for some types of IPD adjustment mechanisms, for example, hinge rotation.

### 3. Tolerance for Vertical Misalignment

Vertical misalignment of the two optical axes or sides of an HMD shall not exceed, for any setting or adjustment within the IPD range, 3.4 arc minutes (Gold, 1971).

Vertical misalignment is the tilt of one optical axis relative to the other, i.e. one axis points up or down relative to the other.

Vertical misalignment is usually measured in minutes of arc. Visual comfort with extended viewing, for some observers, requires less than 5 arc minutes of vertical misalignment (Gold, 1971; Farrell and Booth, 1984). The 3.4 arc minutes recommended as a maximum may be a bit stringent, and up to 5 arc minutes may be acceptable for most observers. Farrell and Booth (1984) would allow up to 10 arc minutes. See Table 2.

4. Tolerance for Horizontal Misalignment

Horizontal alignment of the optical axes of a binocular HMD shall be such that the maximum convergence required of the user shall not exceed 8.6 arc minutes (Gold, 1971), and the maximum required divergence shall not exceed 3.4 arc minutes (Gold, 1971). These amounts of misalignment shall not be exceeded for any setting within the range of adjustment of the IPD. Preferably, parallelism should fall within the range of 0 arc minutes of eye divergence to 3.4 minutes convergence.

When horizontal misalignment is present in a binocular HMD, the optical axes are not parallel, but converge or diverge, i.e., point in or out. Observers can tolerate some eye convergence with binocular instruments, but divergence of the eyes is much less tolerable and only a little divergence is physically possible. Gold and Hyman (1970) and Gold (1971) allow up to 3.4 arc minutes divergence, 8.6 minutes convergence for comfort with extended use. Genco (1983) would permit up to 8.8 minutes of convergence and up to 4.1 minutes of divergence for an observer. Some other authorities (see Table 2) allow more eye convergence, and some allow more divergence, but only the values given by Gold and Hyman and by Gold are based on comfort with extended use. Farrell and Booth (1984) permit no eye divergence, but would permit up to 2.7° of convergence.

5. Tolerance for Rotation Difference

Rotation difference shall be small enough to produce, at the edge of the FOV, not more than 3.4 arc minutes of vertical misalignment anywhere within the IPD adjustment range (Gold, 1971). Vertical misalignment due to a rotation difference may be acceptable for many observers when as large as 10 arc minutes (Farrell and Booth, 1984).

A rotational difference is present when the scene presented to the observer's right eye is rotated with respect to the left eye scene, i.e., one image is tilted sideways or twisted with respect to the other. Rotation difference is sometimes called image twist.

As may be noted from Table 2, authors differ appreciably in tolerance limits for rotation difference, from Johnson's "... rotation difference can not be tolerated", and Gold and Hyman's "keep it to a minimum", to Farrell and Booth's (1984) recommendation of a rotation difference producing no more than 10 arc minutes of vertical misalignment. The present document recommends the tighter tolerance of Gold (1971).

A rotation difference produces both vertical and horizontal angular misalignment, with the angular size of the misalignment increasing with both the amount of rotation and the distance from the center of the field of view. Thus, the maximum permissible rotation difference between the two images or fields of a binocular HMD is smaller with larger fields of view. Since observers are more sensitive to, and can tolerate less, vertical misalignment than horizontal misalignment, tolerance for rotation difference is based on vertical misalignment tolerance. The rotation difference must produce, at the edge of the common or overlapping portion of the scene, a tolerable vertical misalignment. There are, obviously, no tolerance limits for parts of the fields that do not overlap.

The rotation difference, D, for which vertical misalignment, at the edge of the FOV (for 100% overlapping scenes), is K arc minutes is derived in Appendix A and is given by the formula:

$$R = K/\sin(F/2) \qquad \text{Eqn. (1)}$$

Where:

R = Maximum permitted rotation difference in arc minutes.

= Rotation difference causing K arc minutes of vertical misalignment at the edge of the FOV.

F = Angular FOV in degrees.

The maximum permissible rotation difference for binocular HMDs for fields of view of $40^{o}$ through $105^{o}$ is given in Table 3. Values are in minutes of arc, as calculated from equation (1).

6. Tolerance for Magnification Difference

The maximum magnification difference between the images on the two sides of a binocular HMD shall be a difference which produces, at the edge of the common or overlapping area, a vertical misalignment of less than 10 arc minutes (Farrell and Booth, 1984). A value less than 3.4 arc minutes (Gold, 1971) is preferable.

A magnification difference between the two sides or images of a binocular instrument is present when the same object in the field of view has a larger angular subtense at one eye than at the other: the two images are of unequal size. This size difference can cause difficulty in fusing the images, and it causes space distortion. Both vertical and horizontal misalignment is also produced over most of the field of view by a magnification difference. Since observers are more sensitive to, and are more bothered by, vertical misalignment than horizontal misalignment, magnification tolerance is based on the maximum permissible vertical misalignment.

Table 3

Maximum Rotation Difference Tolerance
for not Exceeding Permissible Vertical Misalignment

| TOTAL FOV = F | Max. Rotation Difference F & B* | Gold** | TOTAL FOV = F | Max. Rotation Difference F & B | Gold |
|---|---|---|---|---|---|
| 20° | 58 | 20 | 60° | 20 | 6.8 |
| 25° | 46 | 16 | 65° | 19 | 6.3 |
| 30° | 39 | 13 | 70° | 17 | 5.9 |
| 35° | 33 | 11 | 75° | 16 | 5.6 |
| 40° | 29 | 10 | 80° | 16 | 5.3 |
| 45° | 26 | 8.9 | 85° | 15 | 5.0 |
| 50° | 24 | 8.0 | 90° | 14 | 4.8 |
| 55° | 22 | 7.4 | 95° | 14 | 4.6 |

* F & B = Farrell and Booth (1984). Max. vertical misalignment of 10 arc minutes.
** Gold = Gold (1971), maximum vertical misalignment of 3.4 arc minutes.

NOTE: This table applies to totally overlapping FOVs.

With a magnification difference producing 10 arc minutes of vertical misalignment, some sensitive observers will experience visual discomfort and even headache. MIL STD 1472C (1981) says that magnification difference for binoculars should not exceed 5%. Farrell and Booth (1984) say that magnification difference should not produce more than 10 arc minutes of vertical misalignment. MIL-HDBK-141 (1962) says the the magnification difference should not exceed 2% and that 5% usually precludes binocular vision. For large FOVs, tolerance limits will be smaller in terms of percent size difference, for larger angular vertical misalignments are present at the edge of the overlapping FOVs.

Small differences in the size of lens or prism retaining rings or holding fixtures can cause small differences in the size of the viewed field without causing a magnification difference, Such vignetting or image cut-off) differences can be minute, but, when tolerance limits are small, cause field size differences that are appreciable in relation to tolerance limits.

Not all of the difference in field size, then, may be attributable to a magnification difference. Thus it is not appropriate to measure the angular size of the apparent visual fields and take the difference as a measure of magnification difference: a more complex procedure is necessary. One must measure the angular deviations of corresponding points or objects in the images.

The vertical angular distance of any point (or object's image) from the right side optical axis should differ from that of the corresponding point (or object's image) on the left side by no more than 3.4 arc minutes (Gold, 1971). Farrell and Booth (1984) would permit up to 10 arc minutes.

If K arc minutes is used as a limit on vertical misalignment, a formula may be derived to calculate the allowable limit on magnification difference as a percent. The formula, derived in appendix A, is:

$$d = K/F \qquad \text{Eqn. (2)}$$

Where:

d = Maximum permissible magnification difference in percent.

K = 33.3 for 10 arc minutes or Farrell and Booth (1984)
11.3 for 3.4 arc minutes of vertical misalignment (Gold, 1971).

F = Angular field of view of eyepiece in degrees.

Some tolerances for magnification differences as a percentage of field of view for fields of $40^\circ$ to $105^\circ$ are listed in Table 4. Values are given for both 10 arc minutes (Farrell and Booth, 1984) and 3.4 minutes (Gold, 1971).

7. Tolerance for Luminous Difference

The luminance difference between the images viewed in the two sides of a binocular HMD shall be less than 25%, and, preferably, less than 10%.

The two images, particularly the images originating from two different CRTs or other devices, may easily differ in luminance.

Luminance difference of the two images, as a percent, may be calculated in various ways. For tolerance purposes, and to avoid misunderstanding, luminance difference will be calculated as 100 times the luminance difference divided by the luminance of the more luminous side:, i.e., $100(L_2 - L_1)/L_2$. It will be sufficient to measure luminances for a small area in the center of the FOV, measures being taken from the position of the observer's eye, i.e., looking through the optics.

Farrell and Booth (1984) say that luminance difference should be less than 50%, preferably less than 25%, for binocular instruments. MIL-HDBK-141 (1962) says that the luminance difference in binocular instruments should not exceed 10%. Since this 10% was specified for binoculars, where less than a 10% difference is easily achieved, the MIL-HDBK specs may be a little stricter than necessary.

Table 4

Maximum Permissible Magnification Difference for Binocular Helmet-Mounted Displays

| FOV F | d* in minutes F & B** | Gold** | FOV F | d in minutes F & B | Gold |
|---|---|---|---|---|---|
| 40° | .83 | .28 | 75° | .44 | .15 |
| 45° | .74 | .25 | 80° | .42 | .14 |
| 50° | .67 | .23 | 85° | .39 | .13 |
| 55° | .61 | .21 | 90° | .37 | .13 |
| 60° | .56 | .19 | 100° | .33 | .11 |
| 70° | .48 | .16 | 105° | .32 | .11 |

* d = Rotation difference in ~~aer~~ arc minutes = 3.33 V/F;
V = Maximum vertical misalignment in minutes, F = FOV in degrees.

** F & B = Farrell and Booth (1984), V = 10 arc minutes;
Gold = Gold (1971) recommendation, V = 3.4 arc minutes.

8. Collimation Tolerance

In the absence of research data, a tolerance is provided that is realistic and may be somewhat conservative.

The HMD collimation shall be such that the optical distance to the displayed image shall not be less than 100 meters or greater than optical infinity for either side of the device. Within this 100 meters-to-infinity range, no tolerance on collimation difference between the two sides is required.

In optics there are two distinctly different meanings of the term "collimation". Which one is intended is usually inferable from the context. One meaning is that the optical axes of a binocular instrument are parallel. The other meaning is that the displayed optical image is at optical infinity, i.e., the user's eyes must focus for a very distant object. Parallelism of the optical axes is usually meant when binoculars are collimated. For optical gun sights and other head-up displays, including HMDs, collimation means adjusted to produce images at optical infinity. Thus, an HMD can be "collimated" even though the two optical axes are not parallel, i.e., are out of alignment. A non-binocular telescope for use by only one eye is said (Jacobs, 1943, page 201) to be collimated when the optical and mechanical axes have been brought into alignment. When a vehicle has a thick curved windscreen, objects are displaced from their actual directions by different amounts for the two eyes, so that some adjustment of collimation and of alignment may be advisable.

9. Eye Relief

The eye relief of an HMD, either monocular or binocular, shall be at least 20 mm, and, preferably, 25 mm. A value of 20 mm will cause difficulty for some spectacle wearers, while 25 mm will accommodate 95% of spectacle wearers (Farrell and Booth, 1984).

Eye relief is the distance from the last physical surface of the HMD optics to the exit pupil where the pupil of the eye is placed. It is not, as one might surmise, the distance from the last physical surface to the cornea of the eye, but a few millimeters less. Jacobs (1943, page 195) gives value of about 2 1/4 mm less than the cornea-to-optical device distance. Farrell and Booth (1984) cite values from the literature that average about 3.1 mm. The 2 1/4 mm may be the optical distance, while the 3.1 may be the physical distance. In determining eye relief the optical difference is the one to use.

10. Exit Pupil

For HMDs that have an optical exit pupil, the diameter of the exit pupil shall be at least 10 mm.

The exit pupil, or Ramsden Disc, of an optical instrument is the cross section, at its narrowest, of the bundle of light rays from the last optical surface of the instrument. The light rays from the instrument converge toward it, and diverge past it. The pupil of the observer's eye and the exit pupil of the instrument usually coincide in space. When the two pupils are of the same diameter, coincidence allows all of the light from the eyepiece to get into the eye. When the exit pupil diameter exceeds the eye pupil diameter, there is some room for the eye to move away from the optical axis of the instrument (up, down, sideways, etc.) and to move toward or away from the eyepiece, without loss of retinal illuminance or loss of any part of the field of view. The volume within which the eye can move without loss is usually called a "motion box". How much larger the instrument's exit pupil should be than the eye pupil depends upon the conditions of use. Larger exit pupils are obtained at a cost of volume and weight.

Since the skin on the head can move a little, even a tight helmet does not entirely eliminate motion of the HMD with respect to the eyes, especially when the observer is undergoing severe acceleration during maneuvers or is subjected to vibration and buffeting. Since these are present in the airborne environment, for airborne use an HMD must have an exit pupil appreciably larger than the largest expected size of the eye pupil. A value of 10 mm seems to be a reasonable compromise between a desire for a large exit pupil and a need to minimize the size and weight of HMD optics.

## EYE VERSUS INSTRUMENT TOLERANCES

Reading the technical and scientific literature on alignment tolerances reveals that different authors sometimes use different terminology for convergence and divergence. Some, a small minority, talk about instrument optical axis convergence toward the face or toward the observer. Authors usually talk about convergence toward object space or the viewed space, i.e., away from the observer. Convergence of the optical axes away from the observer requires him to diverge his eyes. When reading articles, keep in mind whether the author is talking about convergence away from or toward the observer, and similarly for divergence.

A second and related possible source of confusion or error in using published documents stems from a lack of clearness on the part of some authors in distinquishing between observer tolerances and instrument tolerances. As noted in the above paragraph, the two can be opposite, e.g., instrument convergence requires eye divergence. Also, when an optical instrument has a magnification, M, misalignment of the optical axes, as far as the image is concerned, is multiplied by M. Thus, when M exceeds unity, instrument optical alignment must be more accurate, sometimes much more accurate, than observer alignment tolerance. The formula relating observer tolerance, A, and instrument tolerance, T, when M exceeds unity, is $T = A/(M - 1)$. For example, with a 7 power binocular system, an eye or observer tolerance limit of 10 arc minutes per vertical misalignment would require an instrument optical axes tolerance of $10/(7 - 1) = 1.7$ arc minutes. When measurements are made on the optical images, only the observer's tolerance limits are of concern, no matter what the instrument magnification. Also, it is the relative angular subtense of the external scene versus the angular subtense of the viewed image that determines overall or system magnification. For example, the optics of an HMD may magnify a small CRT image 7 times, yet overall system magnification may be only unity, i.e., image subtense of terrain objects may be the same with or without the HMD.

## APPENDIX A

## PERMISSIBLE ROTATION DIFFERENCE

Suppose that a binocular viewing device has completely overlapping fields of view, i.e., overlap is 100%. Let the device have a total field of view of F degrees. Suppose, further, that the device is in perfect alignment: vertical and horizontal misalignments are both zero, with no rotation or twist of one image with respect to the other. Now, rotate one image by a few minutes of arc, R, so that a rotation difference is now present. All points in the image of one side, except for the center of rotation, are now misaligned, both vertically and horizontally, with respect to the corresponding points in the other image. The degree of misalignment increases with distance from the center of the field of view. The maximum vertical misalignment will be for a point "P" originally on a horizontal line through the center of the field of view. This image point is now at position "C" in Figure 1. Note that, with the counterclockwise rotation shown in the figure, the new location of the image point is now up (vertical misalignment) and to the left (horizontal misalignment) of the former location. Note, also, that, for rotations of only a few arc minutes, the vertical misalignment of "C" is much larger than the horizontal misalignment. The reverse would be true at the top or the bottom of the circular field of view.

Vertical misalignment, V, is considerably less tolerable to an observer than an equal amount of horizontal misalignment, so that horizontal misalignment will be ignored in this look at tolerance limits.

In the figure, the total field of view of the completely overlapping fields is F, and one field is rotated R minutes of arc. For convenience in visualization, the rotation is greatly exaggerated, actually being only a few minutes of arc. Also, some of the triangles in the figure are shown to one side where trigonometric relationships are more obvious. From triangle "A", $BD = d \, Tan(F^*/2)$, and, from triangle "B", $BD = h/Tan \, R$. Equating the two BD values yields $d \, Tan(F^*/2) = h/Tan \, R$. From this equation, $h = d \, Tan(F^*/2) Tan \, R$. Now, in triangle "C", $h = AD \, Tan \, V$. Equating the two h values yields $d \, Tan(F^*/2) Tan \, R = AD \, Tan \, V$. Now, in triangle "A", $AD = d/Cos(F^*/2)$, so that $d \, Tan(F^*/2) Tan \, R = d/Cos(F^*/2) \, Tan \, V$. Cancelling the d values on both sides and rearranging terms yields $Tan \, R = Tan \, V/Tan(F^*/2) Cos(f^*/2) = Tan \, V/Sin(F^*/2)$. Since both permitted rotation, R, and maximum allowed vertical misalignment, V, are only a few minutes of arc, each tangent may, with negligible error, be replaced by the angle in radians, i.e., by the angle in minutes divided by (60)(57.3) or by 3438. With this substitution, the equation becomes $(R/3438) = (V/3438)/Sin(F^*/2)$, i.e., $R = V/Sin(F^*/2)$. Now $F^*$ differs from F by the horizontal misalignment, which is even smaller than V, so that F, the total field of view, can replace $F^*$ with negligible error, yielding:

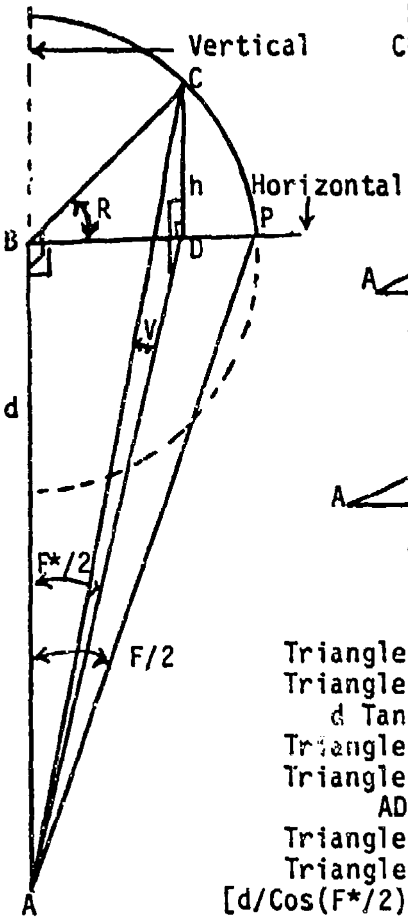
$$R = V/\mathrm{Sin}(F/2) \qquad \text{Eqn (3)}$$

Where:

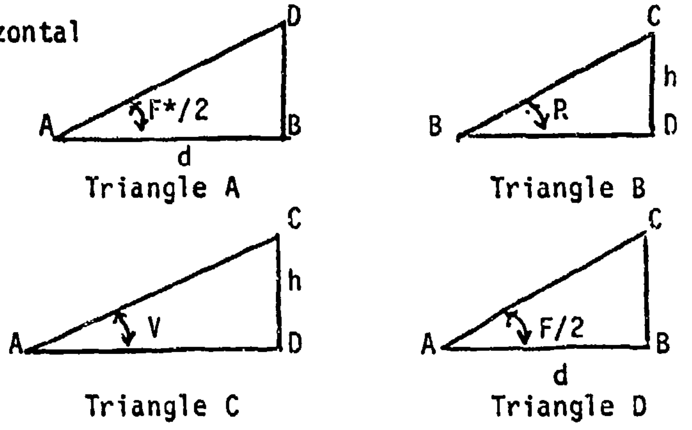
R = arc minutes of field rotation producing V arc minutes of vertical misalignment at the edge of a field of view of F degrees.

For a maximum permissible vertical misalignment of 3.4 arc minutes, i.e. a 3.4 arc minute tolerance (Gold, 1971), V = 3.4 and the equation becomes:

$$R = 3.4/\mathrm{Sin}(F/2) \qquad \text{Eqn (4)}$$




R = Rotation angle; V = Angular vertical displacement;
CD = h = Linear vertical displacement; PD = Linear horizontal displacement; F = Field-of-view;
d = Viewing distance = AB

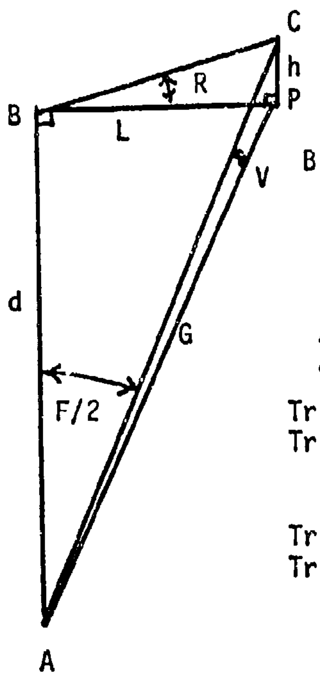


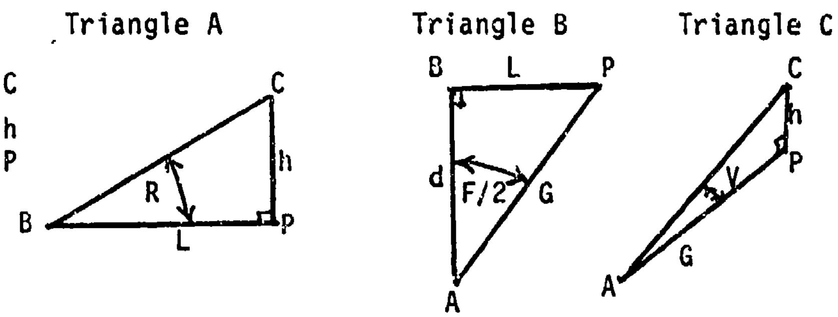

Triangle A $BD = d \tan(F^*/2)$.
Triangle B $BD = h/\tan R$. Equating BD values:
$d \tan(F^*/2) = h/\tan R$.
Triangle C $h = AD \tan V$.
Triangle B $h = BC \sin R$. Equating h values:
$AD \tan V = BC \sin R$ Equation (A).
Triangle A $AD = d/\cos(F^*/2)$.
Triangle D $BC = d \tan(F/2)$. Substituting in Eqn. (A) above:
$[d/\cos(F^*/2)]\tan V = d \tan(F/2)\sin R$, or
$\sin R = \tan V/\tan(F/2)\cos(F^*/2)$. Now:
$F^* = F$, and, with R and V only a few arc minutes,
$\sin R \cong R$ in radians, and
$\tan V \cong V$ in radians, thus,
$(R/3438) = (V/3438)/\cos(F/2)\tan(F/2)$, or

$$R \cong V/\sin(F/2).$$

Figure 1. Geometry for vertical misalignment due to relative rotation, i.e., due to a rotation difference. Rotation difference is greatly exaggerated, being only a few minutes of arc.

A shorter derivation is shown in Figure 2, where it is assumed that, since, for small rotation angles, the arc and chord of Figure 1 are approximately equal and CP is vertical, BPC approaches a right angle as R approaches zero, so the approximation is adequate for small rotations.




Assume CP Arc = CP Chord = h for Rotations, R, of only a few arc minutes.

Triangle A $L = h/\tan R$

Triangle B $L = d\tan(F/2)$. Equating L Values:

$$d \tan(F/2) = h/\tan R, \text{ or}$$

$$h = d \tan(F/2) \tan R$$

Triangle B $G = d/\cos(F/2)$

Triangle C $\tan V = h/G$. Substituting for h and g;

$$\tan V = [d \tan(F/2)\tan R]/[d/\cos(F/2)], \text{ or}$$

$$\tan V = \tan R \sin(F/2)$$

$$\tan V = \tan R \sin(F/2)$$

V and R are only a few arc minutes so that, with considerable accuracy, each may be replaced by its value in radians = (arc minutes)/3484. Thus

$$V/3484 = (R/3483)\sin(F/2), \text{ or}$$

$$R = V/\sin(F/2)$$

For V = 3.4 arc minutes of vertical misalignment tolerance, the tolerance for rotation becomes:

$R = 3.4/\sin(F/2)$ arc minutes maximum rotation difference tolerance.

Figure 2. Alternative derivation for formula for rotation difference tolerance formula. Assumes CP arc and CP chord approximately equal for small rotations.

## APPENDIX B

## MAGNIFICATION DIFFERENCE TOLERANCE FOR COMPLETELY OVERLAPPING FIELDS OF VIEW

When the two sides or fields of a binocular viewing device cover the same image, but one image or field of view (FOV) subtends a larger angle at the observer's eye than the other, there is a magnification difference. To obtain equations relating the variables of interest, assume that the binocular device is perfectly aligned, i.e., the centers of the two fields coincide and there is no rotation or twist. Let the total FOV of the right side or field be F degrees, and assume that there is a magnification difference of d % between the two fields, the left field being larger than the right field in angular subtense at the observer's eyes. The total FOV on the left side is then (1 + d/100) times that on the right, i.e., the left FOV is (1 + d/100)F. The top of the left FOV is higher than that on the right by an amount V, the vertical displacement or misalignment. Similarly, the left FOV extends V degrees below the bottom of the right FOV. The total left FOV is then F + 2V. Equating this to the value given above yields (1 + d/100)F = F + 2 V, from which d = 200 V/F, with f and V both in degrees. For V in minutes of arc, V in degrees is (V minutes)/60, so that d = 200 V/60 F, or:

$$d = 3.33\ V/F \qquad \text{Eqn. (5)}$$

Where:

d is magnification difference as a percent in a FOV of F degrees causing a vertical misalignment of V arc minutes.

If the maximum permissible vertical misalignment in the FOV produced by a magnification difference is 10 minutes of arc, as recommended by Farrell and Booth (1984), the equation above becomes d = (3.33)(10)F, or:

$$d = 33.3/F \qquad \text{Eqn. (6)}$$

Where:

d is the maximum permissible magnification difference between the two FOVs, as a percent, for a FOV of F degrees, that does not cause vertical misalignment to exceed 10 arc minutes.

If the more stringent tolerance limit for vertical misalignment of 3.4 arc minutes recommended for head-up displays by Gold (1971) is used, the formula becomes d = (33.3)(3.4)/F, or:

$$d = 11.3/F \qquad \text{Eqn. (7)}$$

Where:

D is the maximum permissible magnification difference, as a percent, producing a vertical misalignment of 3.4 arc minutes at the edge of a FOV of F degrees.

## APPENDIX C

## MAGNIFICATION DIFFERENCE TOLERANCE FORMULAS FOR PARTIALLY OVERLAPPING FIELDS OF VIEW

In a binocular viewing device there is a magnification difference, K, between the two sides or fields when image details in one side are larger than the corresponding image details in the other side. It is convenient to express K as a percent difference.

If any point in the smaller field is at an angular height, H, above (or below) a line drawn through the centers of the two fields, then the corresponding image point (or same image detail) in the larger field is higher (or lower) by K/100. This vertical difference of corresponding image details is the vertical misalignment, V. Thus, $V = (K/100)H$. Clearly, for a given fixed magnification difference, vertical misalignment increases with image height.

For a field overlap of 50% or less, the geometry of the situation is shown in Figure 3. The maximum image height, H, in the common (or overlapping) area of the two fields or sides is at the intersection of the fields, at the point labeled "C". The angular height, H, of point "C" clearly increases with F, the FOV of one side, and decreases with decreasing field overlap. If vertical misalignment, V, is set at some tolerance value, then the maximum permissible magnification difference, K, is smaller for large angular fields, F, and is larger for small angular overlap, Z.

Let V be in arc minutes, then, from the discussion above, $V/60 = (K/100)H$, so that $K = 1.667\ (V/H)$. The maximum permissible value of K, as given by this equation, is the tolerance for magnification difference calculated from the tolerance in arc minutes for vertical misalignment and the image height in degrees. To calculate magnification difference tolerance for a field overlap of 50% or less, one uses the equation for K and an equation for maximum image height in the overlap (or common) area derived in Table 5. The two equations to use are:

$H = \text{arc Cos } \text{Cos}(F/2)/\text{Cos}(F/2 - Z/2)$
$K = 1.667\ (V/H)$
Where:
H = maximum angular height in degrees of the highest common image point in the overlap area.

K = magnification difference tolerance in percent between the two sides or fields.

F = total FOV of <u>one</u> side or field.

Z = total field overlap in degrees = angular width of the common or overlap area.

V = maximum permissible vertical misalignment in minutes of arc = vertical misalignment tolerance.

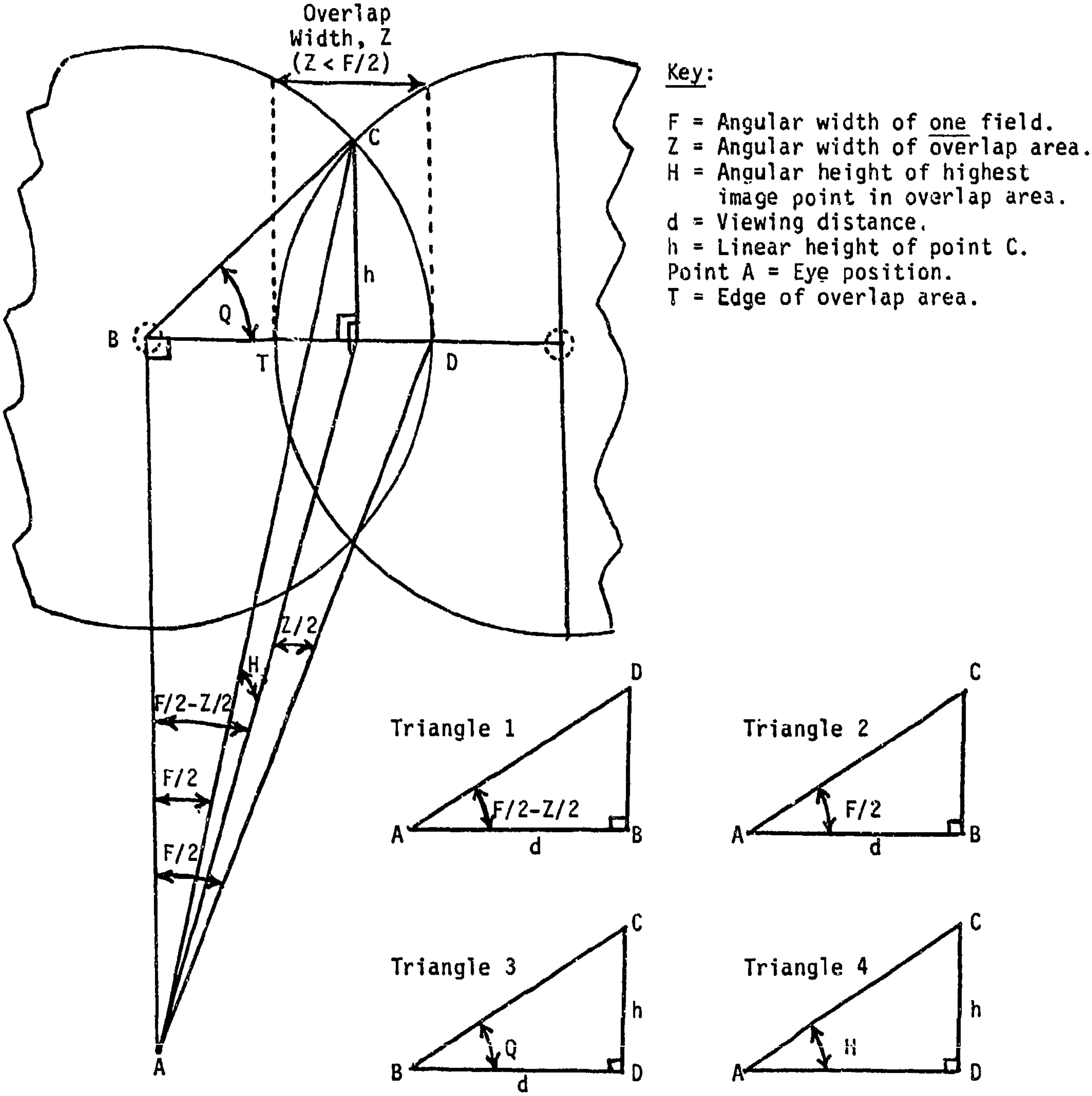



Figure 3. Geometric relationships for partially-overlapping fields of view where overlap is less than 50%, i.e., less than F/2.

EXAMPLE OF PROCEDURE

Let FOV = F = 60°, Z, or field overlap, be 50%, i.e., Z = 60°/2 = 30°, and assume a vertical misalignment tolerance of V = 3.4 arc minutes, as recommended by Gold (1971). Then, H = arc Cos Cos(60°/2)/Cos(60°/2 - 30°/2) = 26.29°, and K = (1.667)(3.4/26.29) = 0.216%. Thus, for the conditions of

TABLE 5

MAXIMUM IMAGE HEIGHT* IN OVERLAPPING OR COMMON AREA

| | | |
|---|---|---|
| Triangle 3 | Tan Q = h/BD, But | |
| | h = AD Tan H. Substituting h: | |
| | Tan Q = AD Tan H/BD = (AD/BD) Tan H, But | |
| Triangle 1 | AD/BD = 1/Sin (F/2 - Z/2). Substituting AD/BD: | |
| Eqn. (A) | Tan Q = Tan H/Sin (F/2 - Z/2) | |
| Triangle 3 | h = BD Tan Q | |
| Triangle 1 | BD = d Tan (F/2 - Z/2). Substituting BD: | |
| | h = d Tan (F/2 - Z/2) Tan Q, or | |
| | h/d = Tan (F/2 - Z/2) Tan Q, or | |
| Triangle 4 | h = AC Sin H. Substituting h: | |
| | AC Sin H /d = Tan (F/2 - Z/2) Tan Q, or | |
| | AC/d = Tan (F/2 - Z/2) Tan Q/Sin H | |
| Triangle 2 | AC/d = 1/Cos(f/2). Equating AC/d value | |
| | 1/Cos(f/2) = Tan (F/2 - Z/2) Tan Q/Sin H. | |
| | Solving for Tan Q: | |
| Eqn. (B) | Tan Q = Sin H/Cos (F/2) Tan (F/2 - Z/2) | |
| | Equating Tan Q of equations (A) and (B): | |
| | Tan H/Sin (F/2 - Z/2) = Sin H/Cos (F/2)Tan (F/2 - Z/2) | |
| | This reduces to: | |
| | Cos H = Cos (F/2)/Cos (F/2 - Z/2), so that | |
| Eqn (C) | H = Arc Cos Cos (F/2)/Cos (F/2 - Z/2) | |

* The derivation is based on Figure 3.

this example, the magnification difference tolerance is less than 1/4 %, a rather small amount. This means that there is a tight tolerance on optical parts: close matching of parts is required, or, with CRTs, precise voltage adjustments are necessary. As a point of interest, with 100% overlap, the maximum value of H is at the top of the field, at $60^o/2 = 30^o$, and K = (1.667)(3.4)/60/2) = 0.19% maximum permissible magnification difference.

## A CAUTIONARY NOTE FOR SMALL FIELD OVERLAP

With small field overlap, magnification difference tolerances should be calculated for both vertical and horizontal misalignment tolerances, and the smaller of the two should be used. With small overlap, horizontal tolerances may be exceeded when vertical tolerances are met.

As noted earlier in the present paper, observers can tolerate appreciably more horizontal misalignment, W, than vertical misalignment, V. Because of this smaller vertical misalignment tolerance, calculation of the maximum permissible magnification difference is customarily based on not exceeding a specified tolerance for vertical misalignment. However, some binocular viewing devices have only a small field overlap (or viewing area common to both eyes). This construction is used to obtain a larger total horizontal viewing area than possible with completely overlapping fields.

When field overlap is small, an amount of magnification difference that produces an acceptable amount of vertical misalignment may produce an unacceptable amount of horizontal misalignment. This point will be illustrated by elaboration of the example presented above that was used to illustrate computation procedure. Note that, in the figure used to derive the formula for H, the maximum horizontal misalignment produced by a magnification difference would be at the edge of the field, at point "T". At this point, horizontal misalignment is W = (K/100)F degrees, or, in arc minutes, W = (KF/100)(60) = KF/1.667. In the example, with a $60^o$ FOV on each side of the instrument and a $30^o$ field overlap, the maximum permissible magnification difference was 0.216%. This produced a vertical misalignment at the highest point in the overlapping (or common) viewing area of 3.4 arc minutes, Gold's 1971 tolerance limit.

In the example, the maximum horizontal misalignment produced by a magnification difference of K percent would occur at the edge of the $60^o$ field, F, and would be W = KF/1.667 = (0.216)(60)/1.667 = 7.77 arc minutes. This number approaches Gold's 1971 tolerance limit for horizontal misalignment of 8.6 arc minutes.

As a point of interest, suppose that field overlap in the example was $20^o$ instead of $30^o$. Then, H = arc Cos Cos($60^o/2$)/Cos($60^o/2 - 20^o/2$) = $22.8^o$, and K = (1.667)(3.4)/22.8 = 0.249% maximum permissible magnification difference based on 3.4 arc minutes tolerance for vertical misalignment. In this case, horizontal misalignment at the edge of the overlapping area is W = KF/1.667 = (0.249)(60)/1.667 = 8.96 arc minutes. Gold (1971) recommends a maximum of 8.6 arc minutes of horizontal misalignment. Thus, while the vertical misalignment tolerance of 3.4 arc minutes is not exceeded by using a K of .249%, the horizontal tolerance of 3.4 arc minutes has been exceeded. Not to exceed the horizonal misalignment tolerance would require that W = 8.6 = (K)(60)/1.667, from which maximum permissible magnification difference would be K = (8.6)(1.667)/60 = 0.239%, not 0.249%.

This example shows that a magnification difference that does not produce an unacceptable vertical misalignment may produce an unacceptable horizontal misalignment. When field overlap is small, then, tolerances for magnification differences should be calculated based on both vertical and horizontal misalignment tolerances. The numerically smaller of the two K values should be used.

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