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MELBOURNE, VICTORIA

SYSTEMS REPORT 25

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by

B. A. J. CLARK and J. E. GORDON

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SUMMARY

Visual approach slope indicators (VASIs) are devices which provide visual guidance to the nominal glideslope for aircraft on approach to landing, the most hazardous phase of flight. Prior to 1981, two VASIs were approved by the International Civil Aviation Organization (ICAO) for use in international air transport operations, the UK Red-White VASIS and the Australian T-VASIS. A new UK development, PAPI, was recently proposed to and accepted by the Visual Aids Panel of ICAO as an additional type of VASI. Red-White VASIS and PAPI both use colour differences between red and white lights as the primary means of coding the guidance signals. T-VASIS uses colour coding only as a secondary separate warning of extreme undershoot. The historical development of signal coding is described in this report with particular reference to VASIs. Colour coding of VASI signals is examined with reference to human colour discrimination ability and the susceptibility of the signals to degradation and falsification by atmospheric and other influences. It is shown that there are several ways (not rare) in which the perceived colour differences between red and white VASI signals can become small enough for the coding to be regarded as failed. In the failed state, the signals may be misinterpreted, resulting in a 'too low' signal being taken as 'too high' with consequent great danger of an undershoot accident. Colour coding of VASI primary signals therefore fails unsafe and it is strongly recommended that VASIs which use it, such as Red-White VASIS and PAPI, should not be used for routine operations by military aircraft in Australia. It is suggested that Transport Australia should consider extension of this recommendation to routine civil aircraft operations in Australia, and, through ICAO, to international air transport operations.

POSTAL ADDRESS: Chief Superintendent, Aeronautical Research Laboratories,
Box 4331, P.O., Melbourne, Victoria, 3001, Australia.

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ABSTRACT

Visual approach slope indicators (VASIs) provide visual guidance to the nominal glideslope for aircraft on approach to landing. Prior to 1981, two VASIs were approved by the International Civil Aviation Organization (ICAO), the UK Red-White VASIS and the Australian T-VASIS. A new UK development, PAPI, was recently accepted by the Visual Aids Panel of ICAO as an additional type. Red-White VASIS and PAPI both use colour differences between red and white lights as the primary means of coding the guidance signals. T-VASIS uses colour coding only as a secondary separate warning of extreme undershoot. The historical development of signal coding in VASIs is described in this report. Colour coding is examined with reference to human colour discrimination ability and the degradation and falsification of VASI signals by atmospheric and other influences. There are several ways (not rare) in which the perceived colour differences between red and white VASI signals can become small enough for the coding to be regarded as failed. The signals may then be misinterpreted, resulting in a 'too low' signal being taken as 'too high' with consequent great danger of an undershoot accident. Colour coding of VASI primary signals therefore fails unsafe and VASIs which use it, such as Red-White VASIS and PAPI, should not be used.

CONTENTS

1. INTRODUCTION

Many aircraft accidents occur in the approach and landing phase of flight (Kraft and Elworth 1968). In the most frequent type of landing accident, the aircraft lands short of the runway (an undershoot accident). Accident investigations indicate that 'pilot error' (i.e. a failure in the man-machine system) is the principal cause of these accidents (e.g. Hartman and Cantrell 1968). The hazard of landing accidents has been recognised since the early days of aviation. Although systematic research into the visual cues utilized by pilots in landing is more recent (see Calvert 1949, 1954, 1955; Lane and Cumming 1956, 1959), the need for visual guidance, especially for night landings, was also recognized long ago. Numerous visual approach aids have been devised in attempts to meet this need. Common examples are the high intensity approach lighting systems which consist of large numbers of flood lamps in a regular array on the ground under the approach path near the runway. The array indicates the location of the runway in poor visibility conditions, assists the pilot to align the aircraft with the runway centre line, and provides a weak cue to glideslope by its perspective appearance. Other ground-based visual approach aids exist which are intended to provide a more precise indication to the nominal glideslope; these are called visual approach slope indicators (VASIs).

Currently, there are two types of VASI approved by the International Civil Aviation Organisation (ICAO) for use in international air transport operations, the UK Red-White VASIS and the Australian T-VASIS, the last S standing for 'system' in both cases. Recently a UK proposal has been put to ICAO for approval of a new VASI, the Precision Approach Path Indicator, PAPI, as an alternative to and eventual replacement for Red-White VASIS. This proposal, now accepted by the Visual Aids Panel of ICAO (Arnold 1981), has led to a series of reports on aspects of VASIs in general and PAPI in particular. The present report is one of three from Aeronautical Research Laboratories on this current topic, the others being Millar (1981a) on PAPI characteristics and performance compared with Red-White VASIS and T-VASIS, and Millar (1981b) on techniques for evaluation of VASIs. In this report, some aspects of the history of VASIs are presented, followed by an examination of colour coding in VASIs with particular reference to PAPI.

2. A BRIEF HISTORY OF VASI DEVELOPMENT

Visual alignment of two or more objects to define direction by elimination of parallactic displacement has been used since and probably during prehistoric times for purposes such as land and sea navigation, territory delineation, weapons aiming and astronomical observations. The kind of objects used for visual alignment has progressively included the following:

(i) natural features such as individual trees and mountain peaks;

(ii) man-arranged objects such as stone monuments (see Atkinson 1978), poles and towers; and

(iii) fires and, more recently, artificial lights (including lasers) to allow guidance at night.

The angular precision of an alignment is dependent, inter alia, on the observer's ability to detect misalignment, e.g. vernier acuity. When the two objects are separated by a small distance s and the distance d of one of them to the observer is large, the alignment angular error $e \approx vd/s$ where v is the observer's acuity threshold angle. (*Observation through a telescope of magnification M may reduce the error to e/M.*) It may be uneconomical or impracticable to arrange two objects with a sufficiently large value of s to give a required value of e, and at some unknown time in the past it was found that shields or masks located close to (or attached to) a single object such as a lamp could delineate azimuth sectors with accuracy largely independent of the observer's acuity, and sufficient for many purposes, with no need at all for a second object to provide a parallax cue. Later, opaque shields, which give light and dark sectors, were supplemented by coloured glass to give coloured sectors. The sharpness of sector boundaries was subsequently improved where necessary by optically collimating the boundary, i.e. an objective lens or mirror is placed with the sector-generating device at its principal focus so that the sector boundary is projected to a more-or-less sharp focus at optical infinity.

Beacons and lighthouses delineating sectors or used in alignment for ship navigation purposes invariably indicate sectors or directions in the horizontal plane. In applying these or other techniques to aircraft glideslope guidance, the primary requirement is for the delineation of paths slanted in the vertical plane.

It is possible that some attempts to use alignment for glideslope guidance took place at least as early as WWI when the need to train large numbers of pilots first developed. However, the authors are not aware of any early references. Alignment, albeit in a conceptually rather complicated scheme, was used in the US Slopeline (or Slopelight) system (see Calvert 1949). In this system, numerous poles tilted slightly from the vertical were positioned on the ground under the approach path so that when the aircraft was on the glideslope, the poles gave the appearance of straight lines intersecting at the aiming point. Departure from the glideslope caused the lines to appear serrated. Each pole had lamps mounted on it to allow use of the system at night. Calvert (1949) described an adaptation of the Slopeline system in which a horizontal line seen between inclined poles indicated aircraft position with respect to the glidepath. Both the Slopeline system and Calvert's adaptation appear too insensitive to glidepath deviation to be of much value and they are presumably now obsolete.

Aircraft carrier landings, especially at night, have long been recognised as one of the most demanding tasks for pilots (e.g. Brictson 1967). VASIs have been used on carriers for at least three decades as a means of lessening the difficulty. In an early form of carrier VASI (Lean 1954) which is now known as the Mirror Deck Landing Aid (MDLA), the image of a central spot of light reflected in a mirror (which has a gyro controlled pitch orientation) is seen aligned with a horizontal row of fixed datum lights when the pilot is viewing from a position on the glideslope. The central spot (the 'meatball') is displaced above or below the datum lights when the pilot views from above or below the glideslope, respectively. A derivation, the Fresnel Lens Optical Landing System (FLOLS) differs mainly in its optical arrangement (Gold 1974). A geometrically comparable system which used vernier alignment of bars transverse to the runway was called the Double Bar Ground Aid, and later, the Precision Visual Glidepath (PVG) (Cumming and Lane 1957) and was developed in Australia for aerodrome use. Various other adaptations and reinventions of alignment-type VASIs exist (e.g. Sparke 1958, Fuller 1968, Spurgeon 1978), including several varieties called POMOLA (Poor Man's Optical Landing Aid) (Dosch 1979).

Optical projector ground aids giving glideslope indications were in use at RAF and some civil airfields as early as 1938 (Sparke 1958). These devices projected vertical sectors of coloured light towards approaching aircraft so that pilots saw a green light near the runway if they were on glideslope, a red light if they were too low, or an amber light if they were too high. These early VASIs had a number of shortcomings such as their limited amount of guidance information and their inadequate light intensity which made them virtually useless by day except at short ranges. Moreover the signals were difficult to identify at night against the background of airport lighting and the equipment failed unsafe when mist or ice formed on the objective lens causing the green and red sectors both to turn amber, the 'too high' signal. Numerous other devices utilizing the basic idea of colour-coded or flash-coded projected sectors have been re-invented from time to time (e.g. Glide Angle Indicator Light, Visual Approach Path Indicator, Pulse Coded Optical Landing Aid) but they all have deficiencies in their ability to convey unambiguous, reliable and appropriate guidance information to pilots (Sparke 1958, H. J. Clark 1968, Gates and Paprocki 1972, Hennessy and Borden 1973, Calvert 1955, 1978; B. A. J. Clark 1979a). For this reason, the various optical projector systems still in use seem mostly to be confined to some navy non-aviation ships (for helicopter operations), army helicopter units, commercial companies operating aircraft in remote locations, and some regional airports.

Not all VASIs fall within the alignment or projector classes of systems. For example, an American system consisting of two flashing lights, set to indicate glideslope and azimuth information by apparent movement between lights (the phi phenomenon, e.g. Kling and Riggs 1971), was evaluated by Jernigan (1966). This Two-Light Landing Approach System was found to have deficiencies in the duration and inter-cycle interval for the two flashing lights and there was confusion with other airport flashing lights. Furthermore, the 2·5 m pole in front of the threshold, directly under the approach path, was judged to be a hazard by pilots (H. J. Clark 1968). Another system based on apparent movement between flashing lights was devised independently by Millar at ARL in 1979 but rejected because the perceived movement was dependent on the angle of view in both azimuth and elevation. A further example of a VASI working on a different principle is the Russian Glissada system (Korolyov and Chuba 1977) in which several steady red laser beams are directed from near the runway to the vicinity of the approach path where forward scattering allows them to be seen by pilots as continuous lines for guidance. Burnham and Fantasia (1979) investigated this type of system and devised variants: it seems that daytime use of these systems would only be possible with laser beams of such power that inadvertent direct viewing of the beams would cause serious eye injury. Yet another example of VASIs working on different principles is the use of patterns on the ground, near the aiming point, arranged to appear as regular geometric figures (e.g. diamonds, Kelly and Bliss 1971) when seen from the glidepath (although it could be argued that this method uses parallax cues). This type of system has been used in tactical military operations (Fuller 1968).

In the early 1950s, development of the Visual Glide Path Indicator took place at the UK Royal Aircraft Establishment (RAE). The current version of this device, known as VASIS but called Red-White VASIS in this paper to avoid confusion with VASIs in general, consists of four sets of light boxes alongside the runway. A set on each side of the runway near the threshold forms a transverse bar and the other two sets form another transverse bar further along the runway. Each box emits red light below the nominal (usually 3°) glideslope and white light above. Between the red and white sectors there is an ill-defined transition zone in which the colour is a mixture of red and white, the proportion depending on the viewing position. The transition zone is geometrically 1·7° wide in the case of slot-type light boxes (Morrall 1960) but often claimed to be effectively only 0·25°. Red-White VASIS defines an acceptable approach channel: from anywhere (within visual range) in this channel, the nearer bar is seen as white and the other red. Below the channel, both bars are red, and above, both are white.

In 1961, ICAO approved Red-White VASIS as an international standard following US Federal Aviation Administration (FAA) adoption of the system for use at civil and military airfields in 1960. A modification of the Red-White system for use in long-bodied aircraft operations, 3-BAR VASIS (Gates 1970), was later accepted as an ICAO standard. Red-White VASIS in 1976 had five ICAO-approved abbreviated forms (AVASIS) with fewer light boxes in each bar. One form has since been deleted. In three of the remaining four forms, the bars are only on one side of the runway. Similarly, in 1976 there were three approved forms of 3-BAR AVASIS, two of which have since been deleted. The remaining form has the bars only on one side of the runway (ICAO Annex 14).

Most of these forms of Red-White VASIS were apparently introduced without adequate testing. However, a Simplified Abbreviated Visual Approach Slope Indicator (SAVASI) consisting of only two Red-White units (i.e. installation only on one side of the runway) and a reduced number of lamps was evaluated by the FAA (Crook 1970). This was a minimum cost system for use at the smaller airports where there is a need to limit the electrical load in the lighting circuits (Gates and Paprocki 1972). An abbreviated Red-White VASIS was also evaluated by Smit (1975) who concluded it to be of no value for light aircraft operations.

Many deficiencies in Red-White VASIS were predicted or reported by Sparke (1958), Baxter and Lane (1960), Baxter, Cumming, Day and Lane (1960), Alexander (1962) and Cumming (1962). Since Red-White VASIS came into widespread usage, these deficiencies have become generally evident (Smith and Johnson 1973). For example, because the aid relies on colour discrimination, in certain atmospheric conditions (such as haze, low sun or low cloud ceiling) when the apparent colour contrast between the red and white light signals becomes diminished sufficiently, the signals become difficult to interpret and potentially misleading.

Although the Australian PVG system proved at least as good as Red-White VASIS in several controlled experiments (Baxter, Cumming, Day and Lane 1960), it had its own shortcomings: its sensitivity could not be optimized simultaneously for long and short ranges, poor atmospheric conditions degraded its sensitivity (Baxter, Day and Lane 1960, Morrall 1960), and some pilots considered the 8-metre frangible poles supporting the lights to be a collision hazard. The PVG was developed in a joint effort between the Department of Civil Aviation (DCA, subsequently Department of Transport, DOT, and currently Transport Australia) and Aeronautical Research Laboratories. A continuation of this joint effort then led to the innovation of using (lensless) projector boxes arranged to indicate glideslope deviation by pattern (or symbol) discrimination. This VASI, called the 'Tee' Visual Glidepath (TEE or TVG), avoided the undesirable features of Red-White VASIS and PVG but incorporated their better features with improvements (see Baxter and Lane 1960). TEE comprised two sets of 6 lighting units arranged in line parallel to and on each side of the runway. Each of the lines was bisected by a transverse bar of white lights. When the pilot was below glidepath, the nearer light units and the transverse bar formed an upright 'T' symbol on each side of the runway signifying 'fly up'. From above the desired glidepath the further light units and bar formed an inverted T 'fly down' signal while for the on-slope signal only the bar lights were visible. The lights forming the leg of the T appeared progressively as the pilot departed further from the desired glidepath, thus providing a stepwise scale of deviation. Separate 'fly up' warning units emitted a red flashing light signal which could only be seen from below the obstruction clearance plane, as in the PVG system.

In 1960 a three-way comparison of TEE, Red-White VASIS and PVG was based on approach profiles calculated from theodolite recordings, and on pilot opinion. Results from both the objective and subjective data indicated that the TEE system provided better visual guidance (Baxter, Cumming, Day and Lane 1960). A subsequent comparative evaluation of TEE and Red-White VASIS by pilot interview resulted in a thirteen to one preference for TEE (Alexander 1962). In 1963 the FAA also compared these two aids and once again, the TEE system was shown to be the more precise and sensitive aid (Hyman 1963). However, it was recommended that TEE should be redesigned to give a better horizontal distribution of light and a clearer gross undershoot signal.

Appropriate small changes to the design of TEE were made in Australia, resulting in an arrangement which has since been called T-VASIS. One of the changes was to incorporate a steady red gross-undershoot signal which appears progressively as part of the 'fly up' signal. T-VASIS has proved extremely effective in practice. A variant of T-VASIS called AT-VASIS (A for abbreviated?) has also been approved by ICAO; it is a T-VASIS with the lights on one side of the runway omitted.

Smith and Johnson (1976) of RAE raised again the issue of serious and well-known faults of Red-White VASIS and emphasised certain of these faults as justification for the introduction of PAPI. Brown (1979) claimed that PAPI was an extension of the Red-White system because it uses combinations of red and white signals for approach guidance. The two systems have major differences, however. PAPI defines an approach sector and indicates angular degree of glideslope deviation by binary information from lights arranged in horizontal bars on each side of, and transverse to, the runway. Three or four red lights indicate 'too low' signals, and three or four white lights indicate 'too high' signals. The 'on glideslope' signal is an equal number of red and white lights. Imbalance between red and white increases stepwise with glideslope angular deviation. The ICAO Visual Aids Panel (VAP) recommended that PAPI should be studied and evaluated as a Red-White VASIS alternative, and eventually, replacement (Recommendation 9/1, VAP Memo/258, ICAO 1978). VAP member countries, UK, Canada, USA, Denmark, USSR, France and Australia, have announced their intention to undertake evaluation of PAPI. The PAPI system was used in operational trials at London/Gatwick Airport in 1977 with a Red-White AVASIS on the left side of one runway and a one-sided PAPI (APAPI?) on the right side. PAPI exists in several forms including a 2-bar version for aircraft with large wheel to eye heights.

An advantage claimed for PAPI is that it is somewhat cheaper to make and install than T-VASIS, although no definite figures have been made available. In response, DOT designed a reduced T-VASIS (RT-VASIS) consisting of six light units on only one side of the runway (Gregson 1978). The production and installation costs of this system were initially estimated to be 40% of the costs for a full double-sided T-VASIS. The design of RT-VASIS as it was proposed to ICAO was initially directed at relatively light aircraft using the smaller country airports (runways of code letter D or E). The VAP recommended that: '. . . the Panel consider the inclusion of specifications for a new reduced T-VASIS in Annex 14 for use on runways of code letter D or E and undertake an evaluation of the reduced system for use on runways of *other code letters*' (Recommendation 9/2, VAP/8-WP/56, ICAO 1978). More recently, however, the major use proposed for RT-VASIS has been as a cheaper alternative to T-VASIS at the larger airports. These proposals were all made when RT-VASIS was in its formative stages, and the most recent examination of the concept has indicated that the cost advantages of RT-VASIS over T-VASIS and especially over AT-VASIS were not as great as originally estimated and that the guidance value is likely to be substantially degraded (Millar 1980, Baxter 1980). RT-VASIS development has subsequently been deferred.

3. SIGNAL CODING IN VASIs

3.1 Primary and Secondary Coding

From the foregoing, it is evident that numerous methods of coding VASI signals are in existence. From the outset in discussing these, it is important to distinguish between primary and secondary (or supplementary) methods of coding, although the distinctions may not always be unequivocal. For instance, colour would normally be regarded as the primary cue in the usual red, amber and green road traffic signals. However, to a person with defective colour vision, the position of the signals (red at the top of the array) and possibly their relative brightness may be the most important, and therefore primary, cues, while hue differences might be regarded as less important and therefore secondary. Primary cues can be defined as the most important in particular circumstances, and secondary cues as useful adjuncts to easy recognition. However, the difficulty of precise classification can be illustrated by another example; with the modern blue 'neutral', brown 'active' and yellow-striped green 'earth' system of coding domestic electrical wiring, colour and pattern might both be regarded as the primary cues to earth wire identification. This example also illustrates how multiple cues can be used to make a situation *failsafe;* regardless of the state of a viewer's colour discrimination ability, the reflectance difference between the yellow stripes and green background will persist with most common light sources so that the earth wire will nearly always have a distinctive appearance.

3.2 Types of Signal Coding

If light from a lamp is prevented from reaching certain directions by an opaque shade or shades, this may be termed directional shielding. This *light/dark* coding is used in harbour beacons, and in T-VASIS where light is emitted from the signal boxes only in the direction allowed by a separated pair of horizontal rectangular apertures or slots. It should be noted that processes such as diffraction and scattering allow a usually minute quantity of light into the geometrical shadow region.

Intensity coding can be exemplified by a system where the intensity of a signal is noticeably different in different directions. Deliberate use of this type of system is not common because it has long been known that absolute judgements of intensity can be unreliable. However, it was used in TEE, and Gates (1970) used it in an unsuccessful version of Red-White VASIS intended for use by long-bodied aircraft. Watkins (1971) described a system, used in France and other countries, which required discrimination between the intensities of three white lights at the apices of an equilateral triangle. Another system used intensity discrimination between four white lights at the corners of a square but it was abandoned after helicopter flight trials had shown the device to be too insensitive (Gross 1965). Unintended and possibly misleading intensity coding is often observable in other signal systems, however, an example being the too-gradual transition between light and dark in some light-dark coded systems (a badly designed lamp-shield combination, or scattering from dust or condensation on a lens in a collimated projection system). Other examples may arise in colour-coded signal systems because of the luminance or intensity difference often consequent on the use of colour coding.

Flash coding, involving temporal rather than spatial variation of intensity or luminance, has proved useful for ship navigation beacons and for aircraft and other anti-collision beacons. Sometimes the light is not completely extinguished in the darker part of the cycle, in which case the 'modulation factor' is less than unity. Flash coding of VASI signals has some undesirable aspects: there may be stroboscopic interference with signals seen through propeller disks, leading to misidentification of the coding, the use of variable flash rate or on/off intervals may be an unreliable cue, and the coding may be difficult to discriminate against a sunlit background. Despite these undesirable aspects, flash coding has often been used in attempts to avoid or supplement colour coding as a primary cue. The sequential flashing of two or more lights in VASIs which use apparent movement for guidance is not a primary cue although it is supplementary in the sense of aiding identification of the VASI against the background of other airport lighting.

Shape, *pattern* or *symbol* coding is frequently used in VASIs as a primary cue (e.g. in the geometrical-figure tactical landing devices and in T-VASIS) and as a secondary cue (e.g. as a consequence of the colour coding and hence intensity coding in Red-White VASIS and PAPI). *Position* coding may be regarded as an aspect of shape or pattern coding. *Alignment* coding, in various aspects, is exemplified as the primary cue in Slopeline, MDLA and FLOLS, PVG, and Glissada. *Movement* coding appears so far not to have been used in VASIs, with the exception of the apparent movement used in the phi phenomenon types. A related usage is in the 'rippling' of lights in some high intensity approach lighting systems. It may even be possible to devise a movement-coded VASI using moire fringes.

Colour coding has frequently been used in VASIs, presumably because it is relatively easy to arrange and because it looks so obvious to most observers in the confines of a development laboratory. Colour coding is a primary cue in Red-White VASIS, PAPI and various multi-sector projector systems. As a secondary cue, colour coding was used in the PVG: the outer bars were coloured amber to aid vernier discrimination between them and the inner (white) bars. A separate flashing red light was visible as a warning of an excessively low approach. Note that the colour cue could have been rendered completely ineffective (e.g. by removing the colour filters from the lamp-boxes) without preventing operation of the PVG. Thus the colour coding of the warning lights in PVG was a secondary cue. Colour coding was used in TEE also as a secondary cue to an excessively low approach, with separate flashing red lights (i.e. flash and position coding) as in PVG. The gross undershoot warning in T-VASIS, however, takes the form of a progressive change of the fly-up signal from white to red, without flashing. Therefore colour coding in this case is a primary cue to a supplementary warning signal, with intensity coding (the red signal being about 1 log unit fainter than the white) as a secondary cue. If the T-VASIS colour coding is rendered ineffective for any reason, the operation of the main guidance signal is unaffected and the supplementary gross undershoot signal may still be recognisable by its intensity coding. Moreover, if the severity of the undershoot is increasing or decreasing, the step changes in intensity may also be evident as a form of flash coding.

Colour coding of the 'meatball' in alignment-type carrier landing systems is another example of colour as a secondary cue. Colour coding is also a secondary cue in the Glissada system, although in this case fortuitously so, as a consequence of the monochromatic nature of the laser beam used.

4. ASPECTS OF COLOUR CODING IN VASIs

4.1 Psychophysical Aspects

4.1.1 Colour vision deficiencies

In Caucasions, about 8% of the males and 0·5% of the females have colour discrimination characteristics sufficiently different from the rest of the population to be regarded as deficient in colour vision. The incidence of colour vision deficiencies varies between races and may be as low as 1% in some races (e.g. Mann and Turner 1956). With the exception of some rare forms such as monochromacy and tritanopia (not further considered here), the deficiency is usually manifested in the anomalous trichromat class (consisting of protanomals and deuteranomals) as a reduced ability to discriminate colours, and as a severely reduced ability, e.g. almost complete confusion of red and green, in the dichromat class (protanopes and deuteranopes). Compared with normals, protans (protanomals and protanopes) have a reduced sensitivity for light at the long wavelength (red) end of the visible spectrum. About 5% of Caucasian males are deuteranomals and the other 3% is made up about equally of deuteranopes, protanopes and protanomals. A concern of this paper relates to those colour defectives who have, one way or another, not been prevented from holding commercial or higher classes of pilot licences. Some countries do not, or at least until recently did not, have any colour vision assessment of civil pilot licence applicants and the standards, tests, and dispensations against the standards set by other countries vary widely (Watkins 1971). Even when tests are done, results depend on the way the tests are conducted (Cole 1963) and there is no doubt that the pilot population did include some colour defectives (Sloan and Habel 1955, Bailey 1965) and presumably still does.

In countries where colour vision tests for pilots are done, the tests frequently take the form of lantern tests where the subject has to name colours produced by filters in front of a lamp. Protans, especially protanomals, may be able to pass some forms of this test by making use of the duller appearance of red lights as a colour recognition cue. Deuteranomals may also be able to pass, especially if their degree of defect is relatively mild. Performance of individuals at lantern tests depends on the kind of test used (Cole and Vingrys 1981), and performance at specific tasks such as recognition of signal colours at sea is not always well correlated with results from other colour vision tests (Kinney, Paulson and Beare 1979). Furthermore, anecdotal accounts of cheating to pass colour vision tests abound among aircrew. Some air forces accept deuteranomals in any case (Watkins 1971), and ex air force pilots are commonly employed by airlines.

As well as the congenital (hereditary) defects of colour vision described above, there are also acquired defects resulting from disease or injury. Chronic exposures to sufficient levels of alcohol or nicotine are among the known causes of acquired defects. Generally the congenital defects are manifested as red-green confusion and the acquired defects as blue-yellow confusion. Acquired defects are generally accompanied by decreases in other visual abilities. The incidence of acquired defects in the (presumably European) population was estimated to be about half as large as the incidence of congenital defects (Lakowski 1969), and while the incidence of acquired defects in a presumably healthier commercial pilot population is likely to be lower, it is also unlikely to be zero.

4.1.2 Physiological effects

It is well known that perception of colour depends strongly on the viewing c[illegible]itions. The colours of aviation signal lights have to be recognised by pilots against a rang[illegible] back-ground luminances ranging from dark to daylight values, and chromaticities ranging f[illegible] skylit green grass to sunlit red desert sand. At night, the cockpit lighting may be red or [illegible] The apparent colour and brightness of signal lights depends on the state of adaptation [illegible]ye. Transient adaptation effects can be of importance in the case of pilots who are altern[illegible] their attention between the instrument panel and the outside view.

Visual tasks subtending less than about 0·5° are affected by 'small field' or foveal tritanopia in which, like congenital tritanopia, blue-yellow discrimination is adversely affected.

Older persons tend to have colour discrimination changes consistent with the yellowing of the crystalline lens of the eye. The appearance of colours is altered, so that, for example, white takes on a yellowish tinge and although this appearance may be compensated by chromatic adaptation, the range of discriminable steps in hue between white and red is reduced. Macular pigmentation also produces colour shifts of white towards yellow and racial differences probably exist in the amounts of lens and macular pigments (Wyszecki and Stiles 1967, p. 420).

4.2 Physical Aspects

The discrimination of colour-coded signals in VASIs such as Red-White VASIS and PAPI can be affected not only by the physiological aspects just discussed but also by the following physical factors.

4.2.1 Incandescent lamps and red filters in VASIs

Compared with the white represented by the chromaticity of say CIE Illuminants C or D, the light from a tungsten-halogen incandescent lamp at rated voltage is distinctly yellowish to a colour normal. The light from a conventional incandescent lamp at rated voltage is even more yellowish. A method often used to reduce light output of aviation ground lighting in keeping with ambient light levels is to lower the voltage supplied to the lamp and this has a further effect in making the colour of the light tend towards orange. The number of discriminable steps in chromaticity between the 'white' and red in a Red-White VASIS or PAPI thus depends on the kind of lamps and on the voltage applied to the lamps. For the red filters used with incandescent lamps to give aviation signal red light, the luminous transmittance (T) is physically limited to less than about 20%, and in practice T may be as low as 10% or 12%. Assuming the correctness of the CIE colorimetric system, neglecting atmospheric absorption and assuming the inverse square law, the visual range of the red lights could be expected to be $\sqrt{T}$ of the range of the unfiltered lights, i.e. about one-third.

4.2.2 Atmospheric effects

VASIs are always observed through some thickness of the atmospheric aerosol which consists of pure air, water vapour, industrial and vehicular exhaust gases and suspended small particles of ash, dust, water, carbon, salt and so on. Pure air by itself is spectrally selective in its transmission but this is not of much significance in the present context. The effect of suspended particles can be of great importance, however; for instance in the commonly dust-laden atmosphere at Darwin, the Red-White VASIS has appeared as an orange-blue configuration (Watkins 1971). (This resulted in the early replacement of the Darwin Red-White VASIS by T-VASIS.) Profound alteration of the apparent colours of signal lights can occur when the suspensoid is monodisperse (i.e. all the particles are of the same size) and this situation, although unusual (e.g. literally and figuratively, once in a blue moon), can arise with smoke from forest fires and volcanic dust (Clark 1973). Much more commonly, haze, mist and fog cause a reddening of white lights by selective scattering of the shorter wavelength component of the signal. The colour shift is similar in direction to the shift introduced by reducing the voltage applied to an incandescent lamp; for instance, Middleton (1952, p. 172) calculated that a typical industrial haze could make a Source A lamp (2854 K) at 1 km distance appear to be a saturated orange colour like a 1500 K lamp. Hald (1980) observed a PAPI white light (nominal colour temperature 3000 to 3100 K) '. . . reduced to about 2000 K by relatively hazy weather' over a 2·5 km light path. For Middleton's example, if the u, v coordinates of Illuminant A and a 1500 K lamp are plotted on a 1960 CIE-UCS diagram (Fig. 1), it can be seen that for colour normals, this change nearly halves the number of just discriminable differences in chromaticity between Illuminant A white and the middle of the ICAO red aeronautical ground lighting range. It also reduces, by approximately the same factor, the intensity difference between a Source A lamp and a similar lamp filtered to produce aviation red. The actual number of just discriminable differences would depend strongly on the viewing conditions. One estimate can be obtained from Figure 6·30 of Wyszecki and Stiles (1967): there are about 20 just noticeable steps in chromaticity between a 4800 K source and a 625 nm spectral source of similar intensity, and transferring this value to Figure 1, the number of steps between Illuminant A and a mid-aviation-red can be estimated as about 17 for the viewing conditions used in generating Figure 6.30. (Note that the viewing conditions appropriate for the data of Figure 6.30 are 2° photometric field and 30 trolands retinal illuminance (low photopic range).) Actual viewing conditions for a VASI may be quite different, viz. brighter and smaller signals, extensive surround. In general, colour discrimination performance in the field may be reduced compared with laboratory results such as those in Figure 6.30. The laboratory results are therefore only a useful guide.)

The foregoing refers to the colour discrimination abilities of colour normals. Dichromats have much poorer performance. Deuteranopes at best can distinguish about 27 steps in chromaticity and protanopes 17. (Compare this with the many thousands of steps which can be distinguished by colour normals.) If the chromaticities of Illuminant A, a 1500 K source and the aviation red boundary are plotted on a 1931 CIE chromaticity diagram which also has the confusion loci for dichromats (Fig. 2, derived from Watkins 1971), it can be seen that Middleton's example of industrial haze reduces the difference between white and red signals from 5 just noticeable steps to nil for a deuteranope and from 2 (at best) to nil for a protanope. Anomalous trichromats, who (as pointed out above) as a class are not rigorously excluded from commercial flying, have colour discrimination abilities intermediate between those of colour normals and dichromats and it can therefore be concluded that industrial haze (like Middleton's example) may make chromaticity discrimination between white and red difficult for anomalous trichromats. Note that the usual intensity difference between white and red signals, an important cue for some colour defectives, is also reduced by industrial haze.

One other effect is appropriate for mention here. The preceding discussion is applicable to the situation when the ambient conditions affect mainly the white light and not red, viz. in twilight or at night. In daytime, the white light can still be reddened by selective atmospheric transmission, but more importantly, a luminous veil of scattered light (i.e. a part of the sky) will be present between the red signal and the observer and in nearly all cases this will tend to desaturate the red signal, reducing both the intensity and chromaticity differences between red and adjacent white signals. This will make the discrimination of the signals more difficult for all observers, colour normals as well as colour defectives. Atmospheric scattering as a cause of observed marked degradation in the colour differences between white and red signals of Red-White VASIS in daytime was suggested by *Smith and Johnson (1973). They did not mention* the possibility that physiological effects may have contributed to the degradation.

4.2.3 Effects of dust and condensation on lenses

If an objective lens is used to collimate colour-coded or light-dark coded sector signals in a projector system (as opposed to lensless slot-type systems), the lens may, in communications terms, increase the 'cross-talk' between the sectors. In the case of collimated light-dark systems like certain lens-type T-VASIS boxes of non-Australian origin, for example, multiple reflections within the lens and scattering from dust and imperfections on the lens surfaces slightly reduce the amount of light in the 'on' sector, and, much more importantly, redirect some light into the 'off' sector where it may give a confusing indication, especially at night. This aspect was criticised in a FAA test of T-VASIS using lens-type light boxes, although the overall assessment was outstandingly favourable (Jones 1977). False signals from T-VASIS lens-type boxes were also brought to notice by ICAO (1978, VAP-WP 14 Appendix A). Smith and Johnson (1976) described an anecdotal account of similar misleading signals from T-VASIS installations, almost certainly due to the use of lens-type boxes, but erroneously ascribed by them to inaccurate alignment of the boxes. Although lens projection appears attractive in terms of utilizing more of the lamp output and reducing the size of the light boxes by comparison with lensless projection, it is false economy and was recognised as such by the originators of T-VASIS. It was also recognized long ago by Calvert (1978) in connection with colour-coded VASIs:

> 'It is natural for illumination engineers to use lenses because a higher intensity can be obtained for a given voltage, and also sharper divisions between the colours. For these reasons we ourselves used lenses in the old three colour Angle of Approach Indicators. We were, however, unable to prevent the colours mixing when ground mist was present and when poor maintenance caused the surface of the lens to become coated with dirt or moisture. As we regarded the complete absence of false signals at *all* times to be the over-riding operational requirement, we therefore eliminated the lens. We were able to do so because an absolutely sharp division between the colours is not as important operationally as the absence of false signals. Furthermore, the increase in intensity does not increase the range to a significant extent in poor visibility; in good visibility an adequate range can be obtained without the use of a lens.'

With colour-coded systems, the principal effect of lens scattering is the reduction of the colour differences between the signals. For instance, in a red-white coding scheme, the white signal becomes reddened and the red becomes desaturated, i.e. pink. Because the scattering is angle-dependent, the greatest effect is adjacent to the direction of the transition between the colours. The magnitude and angular variation of the effect depends on the cause of the scattering, viz. lens surface reflections, or dust-water deposits, and in the case of particulate scattering, on the size distribution and optical properties of the particles. Hald (1980) reported water condensation on both sides of the objective lenses in trial PAPI installations. The resultant scattering '. . . totally destroyed the signal, so that the light received over a certain distance happened to be only white with no red sector. In an operational system this will mean that the PAPI system would only give a full "fly down" signal at all angles.' Electrical heating elements have been installed near the lenses in some PAPI boxes in an attempt to overcome the condensation problem. The heaters will not overcome the dust problem: if anything they will exacerbate it because of the extra airflow over the lenses as a result of convection currents.

4.2.4 Effects of windshields and spectacles

It is not uncommon for aircraft windshields to be spectrally selective in transmission of visible light (Clark 1972). It is common for sunglasses, including those used by pilots, to have selective transmission also (B. A. J. Clark 1968), with possible serious consequences for the detection and recognition of red signals in particular. Australia appears to be the first country with a sunglass lens specification which places specific limits on alteration of red signal appearance (SAA 1971); however, compliance with that specification is voluntary, and standards of other countries may not exclude lenses which profoundly degrade red signal perception (Clark 1970). The effects of viewing through spectrally selective sunglasses and windshields in combination may be additive in degrading perception of red signals. For colour normals, the degradation may take the form of changing the intensity difference (and hence visual range difference) between red and white signals as well as changes in the chromaticity difference. For colour defectives, such changes are likely to be of greater consequence in altering detection distances and causing errors of recognition.

Veiling glare from optical imperfections, scratches, dirt, raindrops, reflections and fluorescence in windshields and spectacles has the effect of reducing the apparent contrast of distant objects (Clark 1979 b). In the case of red and white signals seen in daylight, veiling glare reduces the chromaticity and intensity differences, thus tending to make discrimination more difficult for colour normals and especially so for colour defectives. Light scattering within the eye has a comparable effect.

4.3 Combinations of Effects

The degradation of red-white signal discrimination by combinations of physical and physiological effects tends to be additive. Scattering of the light from the signal units may be caused by dust and/or condensed water on projector objective lenses, in the atmosphere, on the aircraft windshield and on any spectacle lenses used by the pilot. The total effect is to reduce the intensity of the signals and to reduce the intensity and chromaticity differences between the signals. Veiling glare, caused by scattering of non-signal light such as sunlight or skylight into the light path from signal to pilot can also arise from the same scattering processes and can further reduce the intensity and chromaticity differences between the signals. Spectrally selective transmission and scattering anywhere in the light path tends to make matters worse. For example, reddening of the white signal by industrial haze, coupled with desaturation of the red signal by scattered daylight and then observation through brown-tinted sunglasses (which would further reduce the difference between white and red), illustrates how these effects compound. At night, the sunglasses and daylight will be absent but reduction of the signal intensity to night levels by reduction of lamp current may have a serious further reddening effect on the white signal.

Whatever difficulties may have to be faced by colour normals in recognizing coloured signals under adverse conditions, the problems can nearly always be expected to be worse for colour defectives.

5. PHOTOMETRIC STUDIES OF T-VASIS AND PAPI

5.1 Arrangement of Equipment

A PAPI projector box from the first batch to reach Australia, in March 1981, was made available briefly for laboratory studies. (There are several manufacturers of PAPI boxes. The characteristics of the various makes of PAPI boxes are not greatly different, judged from trade literature.) Photometric measurements were made with the PAPI box and a T-VASIS box side-by-side to allow comparison of some important characteristics. The size of the laboratory precluded working in the far field of the two boxes and this prevented measurements near the edge of projected sectors. The near field output of the boxes was projected onto a matt white surface 7·5 m distant from the output slot of the T-VASIS box or from the poles of the PAPI objective lenses. The photometer was a Pritchard Model 1980. A magnesium carbonate reference matt white surface of known reflectance was used in converting luminances measured at the screen to the values for a perfectly reflecting screen. These values were then converted to source intensities by standard photometric formulae.

The Fisher and Crouch (1968) corrections for non-neutrality of the 'neutral' filters in the Pritchard photometer were not applied to the measurements of red filters because their photometer was an earlier model: the absence of corrections may be a source of error in the results reported below. Furthermore, the 'photopic' filter calibration curve supplied with the instrument shows departures from the CIE photopic luminosity curve and this causes the photometer response to red lights to be only about two-thirds of the real value. Again the red filter results reported have not had corrections applied. Therefore the ratio of red to white luminances for individual boxes will be underestimates of the actual luminous transmittances of the red filters.

The standard lensless T-VASIS box is fitted with four 100 W incandescent sealed-beam lamps for daytime use, and two 35 W incandescent sealed-beam lamps of greater horizontal beam spread for night use. The signal intensity is controllable to appropriate values by controlling the lamp current, and the provision of separate day and night lamps avoids excessive reddening of the primary white signal which would otherwise be a consequence of trying to cater for the whole day-night range by dimming just the day lamps. The photometric measurements were made with the lamps operating at rated conditions: 6·6 A for the day lamps and 2·9 A for the night lamps.

The PAPI projector box was fitted with three 200 W tungsten-halogen incandescent lamps each mounted at the focus of a separate paraboloidal reflector. The red filter intercepted the top half of each of the three collimated beams from the reflectors. Three plano-convex singlet lenses collimated the horizontal edge of the red filter to produce the output signal. It was noted that the PAPI optical system produced extreme curvature of field, the focal distance for the red-white transition at the edge of the projected field being only a few metres instead of optical infinity. Measurements were first made with the PAPI lamps operating at rated current and were then repeated for a series of reduced currents considered to represent an appropriate range in practice.

The spectral transmittance of the PAPI filter in the visible spectral region was measured with a Shimadzu MPS 50L spectrophotometer.

5.2 Photometric Results

The results for T-VASIS are given in Table 1, and for PAPI in Table 2. Comparison of these tables indicates:

(a) PAPI white signals have about four times the intensity of T-VASIS day signals at rated current, which gives about double the visual range for seeing the light (but not necessarily for interpreting the signal correctly).

(b) PAPI red primary signals are more than one and a half times as intense as T-VASIS day red secondary warning signals.

Taking (a) and (b) together indicates that the red filters in PAPI have a relatively lower luminous transmittance than those in T-VASIS (which are known to have T ≈ 15%) This was confirmed when the luminous transmittance, T, and the chromaticity coordinates of the PAPI filter for CIE Illuminant A were calculated from the spectrophotometric curve. The value of T was 8% which is remarkably low, considering the chromaticity of the filter (which is plotted in Figs 1 and 2). For the same chromaticity, practical red filters exist with T 12% or more, approaching the theoretical limit of 14% found using the theory of optimal colours (Wyszecki and Stiles 1967, p. 341).

In practice, the range of intensities required for T-VASIS in Australia is 300 to 1. The night lamps allow this range to be achieved without the white signal dropping below a correlated colour temperature of about 2100 K. Because the PAPI box tested was brighter than the T-VASIS box at the high end of the intensity range, it should presumably be required to operate over a range of 1200 to 1. In Table 2, the intensity of the PAPI white signal varies with about the 6·5 power of current so that a current of about 2·22 A would be required, and extrapolation of the colour temperature results in the Table indicates that the dimmest required setting of the white signal would give a colour temperature of below 1800 K.

5.3 PAPI Performance with Dusty Lenses

Allen (1974) used fuller's earth (aluminium silicate), applied by spraying as a suspension in alcohol, in simulating road dirt on motor vehicle windshields in experiments on scattered light effects on vision. Although Allen recognized shortcomings of this method, the results proved satisfactory. In the present work, dust deposits on PAPI objective lenses were simulated by talcum powder (magnesium silicate) applied to the lens outer surface with a paper tissue. Again, the simulation has shortcomings but is considered sufficiently realistic for the present purposes. Table 3 gives the photometric results. By comparison with the results in Table 2, it can be calculated that the direct transmittance of the powder layer was about 0·63 which is not unrealistically low.

The measurement at 0·7° (Table 3) was as close to the centre of the out-of-focus transition line between the colours as possible outside the overlap of the red and white images. Naturally, at this position the scattered light effects were greatest. The red scattered light had a small effect in reddening the white sector, judged from the correlated colour temperature, but the effect of the white scattered light in the red sector was profound: the light was no longer red but pink, principally because the white scattered light originated from the white sector which was an order of magnitude more luminous than the red sector. For the lamp at rated current, the measurements at 2° from the transition zone centre show a lesser, but still important, whitening of the red signal. The second row of measurements at 2° indicates that the combined effect of scatter and reduced filament current is less in the case of the red signal but now more important in the case of the white signal. Overall, the colour difference between white and red signals is least with the combination of effects. Put another way, with the lamp at rated current, the dust on the lens reduced the chromaticity difference between red and white signals to about a sixth or less of the value for a clean lens. The combined effect of the dust and lowering the lamp current was to reduce the original chromaticity difference to about a twelfth.

5.4 Discrimination and Reliability of PAPI Signals

As indicated in Section 4.2.2, for colour normals at best there may be only a few tens of just discriminable steps in chromaticity between equally intense white and red signals of the sort used in VASIs. Differences in intensity increase the number of discriminable steps by adding another dimension to the colour difference. In the PAPI box examined, the red filter was much lower in luminous transmittance than those used in T-VASIS and this suggests an attempt to increase the number of steps by the use of a purer, darker red. The gains made in this way are not large, however; perhaps an extra few steps in chromaticity and in intensity. The accompanying loss in range of the red signal may be important. As an example, comparing filters of 15% and 8% transmittance, the darker filter has about 27% less visual range. Another disadvantage of using darker filters is that the red signal is more easily overcome by scattered white light, either ambient or from the white signal. In fact the suggestion has been made that the white signal ought to be reduced in intensity to the level of the red signal by the addition of neutral density or light-blue filters (Smith and Johnson 1973). If this were done, however, the range of the white signals would be reduced to about one-quarter and this would also eliminate the intensity difference used as a colour recognition cue by some colour defectives and colour normals when the chromaticity differences between the signals have been reduced greatly by scattering and/or reduced filament current.

The PAPI box examined did not have neutral density filters or any other means to equalize the red and white signal intensity. The white signals will therefore be visible for about four times as far on approach as the red signals. PAPI proponents have claimed that if one, two or three lights only can be seen, or can be seen brighter than the complement of the set of four then the missing or fainter lights must be red and the signal is interpreted accordingly. This could actually lead to a most hazardous situation: consider a pilot making an unintentionally low approach in circumstances in which the chromaticity difference between the red and white signals is small. Airport lighting will have a reddened appearance. The four desaturated red or orange-red signals will come into view and the pilot may believe that they are the full 'too high' signal rather than the 'too low' signal. The false signal indication may be made even more compelling if one of the outer boxes in a single side of the runway installation has a lamp failure: the other two lamps in that box will continue to operate but the total light output will be reduced, so that the pilot may still think he is seeing a 'too high' signal, with an indication that his misperception of the brighter lights as white is correct. These effects are additional to the false 'too high' signal reported by Hald (1980) and mentioned above in Section 4.2.3.

There is therefore a strong prima facie case that PAPI signals are not always reliable for colour normals, that they are less reliable for colour defectives, and that they are not failsafe.

5.5 Improving T-VASIS Range and Angular Coverage

As a by-product of the photometric studies, it was noticed that much of the light output from the sealed beam lamps in the T-VASIS slot-type box was intercepted by the opaque parts of the exit slot. For greatest efficacy of a slot-type box, the rear slot (nearest the lamp) should pass most of the light output of the lamps. This was the case in the box examined, which had the red filter that gives the secondary 'fly up' warning occupying about the upper two thirds of the total vertical extent of the rear slot. In vertical extent, the exit slot was of necessity only about one third the size of the lamp aperture so that the slightly diverging output from the lamp was largely intercepted. If the reflector to filament distance in the lamps could be increased slightly without altering the reflector curvature, it would be possible to focus the filament images within the exit slot, thereby increasing the signal intensity. Specially made sealed beam lamps are likely to be too expensive for this application but separate lamps and reflectors as in the PAPI box examined could easily be adapted.

With the T-VASIS box as supplied, the principle was tested by placing a weak positive lens between one of the lamps and the rear aperture. This had approximately the desired effect and increased the on-axis signal intensity by 31% despite the 8% reflection loss of the lens. Fitting of suitable lenses to existing boxes may be simpler than changing the type of lamp and fitting reflectors. It should be noted that lenses in the position described can have no effects of practical significance on the precision of the signal cut-off angles nor on the freedom from false signals which is a proven characteristic of T-VASIS slot-type boxes.

One of the minor criticisms occasionally directed at T-VASIS is that the pattern 'breaks up' several seconds before touchdown. A few more seconds of visibility would apparently assist in overcoming this criticism which is largely a result of the present limits in horizontal angular range of the T-VASIS boxes. Inspection of the box used in the photometric studies indicated that the angular range could be increased simply by the addition of a vertical mirror to the inside of the box on the side remote from the runway. The mirror would need to be aligned carefully, which is not difficult to do, and its surface would need occasional cleaning. Fortunately, the mirror could be rear-aluminized for durability, and dust or condensation on it would not affect the integrity of the signal to any practical extent.

6. DISCUSSION

As discussed by Millar (1981a), PAPI has ergonomic deficiencies, such as the basic transgression of having the display transverse to, instead of congruent with, the direction of control. However the most serious deficiency is probably the perpetuation of the Red-White VASIS debacle of using colour coding as a primary and sole cue to discrimination of the guidance signal. The facts are plain: colour coding per se is unreliable and it fails unsafe. Ergonomics texts repeatedly make the point that colour coding is useless or unsafe as a sole cue. As a secondary cue, subsidiary to a primary cue such as pattern discrimination, colour coding can have a useful place. In T-VASIS, colour coding of the 'fly up' warning is subsidiary to the full 'fly up' signal and it complies with the usual aviation convention of 'red connotes danger'. In PAPI, red is used as part of an 'operations normal' indication. This difficulty could be overcome by using a different combination of colours, but hopefully, enough has been stated in Section 3 to indicate that *any* colour coding system can be degraded by the physiological and physical factors mentioned. The use of colour differences as the primary signal code in VASIs is hazardous and indefensible, and it is within the terms of reference of these laboratories to recommend that VASIs such as Red-White VASIS and PAPI should therefore not be used for routine operations by military aircraft in Australia. (The qualification of 'routine' would still allow colour-coded systems to be used in experiments.) It is suggested that Transport Australia should consider applying a complementary embargo to routine operations by civil aircraft in Australia, and that representations should also be made by Transport Australia for ICAO rejection of Red-White VASIS and PAPI for use in international air transport operations.

7. CONCLUSIONS

Ground-based VASIs have been in use for over forty years. During this time, several new types of VASI have been invented and many re-inventions have also occurred. Prior to 1981, the only VASIs with ICAO approval were Red-White VASIS (in several forms) and T-VASIS. A proposal that a new aid, PAPI, should receive ICAO approval as an alternative to, and eventually as a replacement for, Red-White VASIS was accepted by the Visual Aids Panel of ICAO in 1981. This report is one of several from ARL which are in response to the PAPI proposal.

The issue of colour coding as a primary cue in Red-White VASIS and PAPI was singled out for special attention in this report. Other ergonomic aspects of Red-White VASIS and PAPI in comparison with T-VASIS are treated at length in a complementary report by Millar (1981a). Colour coding as a primary cue is almost universally condemned in the ergonomics literature, and an examination in this report of the numerous factors which act to degrade the reliability of colour-coded primary signals from VASIs supports the view that neither Red-White VASIS nor PAPI should be used in air transport operations. Apart from reasonably common circumstances which render colour-coded signals from these aids as unreliable, e.g. atmospheric conditions, and windshield and projection optics scattering, there is a strong prima facie case that the signals, through combinations of physical and physiological circumstances which are not rare, can become sufficiently misleading to be hazardous. T-VASIS has shape/pattern coding as its primary cue and its colour-coded extreme 'fly up' warning signal is secondary and usefully redundant, and the system is therefore failsafe in all conditions, including those in which Red-White VASIS and PAPI are hazardous. Therefore it is strongly recommended that VASIs such as Red-White VASIS and PAPI which use colour differences as the primary signal code should not be used for routine operations by military aircraft in Australia. It is suggested that Transport Australia should consider extension of this recommendation to civil aircraft routine operations in Australia, and that representations should be made for ICAO to reject the use of Red-White VASIS and PAPI in international air transport operations.

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TABLE 1

Laboratory Photometric Measurements of a T-VASIS Light Box

Condition	White Signal		Supplementary Red Signal
	Intensity cd	Correlated Colour Temp. K	Intensity cd
4 day lamps (rated current)	34 000	3 000	3 400
2 night lamps (rated current)	2 800	2 700	360

TABLE 2

Laboratory Photometric Measurements of a PAPI Projector

Lamp Current A	White Signal		Red Signal
	Intensity cd	Correlated Colour Temp. K	Intensity cd
6·60 (rated current)	120 000	2 950	5 600
5·50	43 000	2 530	2 300
4·80	18 000	2 450	1 100
4·20	7 500	2 220	540
3·70	2 800	2 160	220
3·30	1 200	2 000	100

TABLE 3

Laboratory Measurements of PAPI Projector with Dusty Lens

Angle from Red-White Transition	Lamp Current A	White Signal		Red Signal	
		Intensity cd	Correlated Colour Temp. K	Intensity cd	Correlated Colour Temp. K
0·7°	6·60	75 000	2 940	12 000	2 350
2°	6·60	72 000	2 950	8 200	2 050
2°	3·30	910	1 920	130	1 700

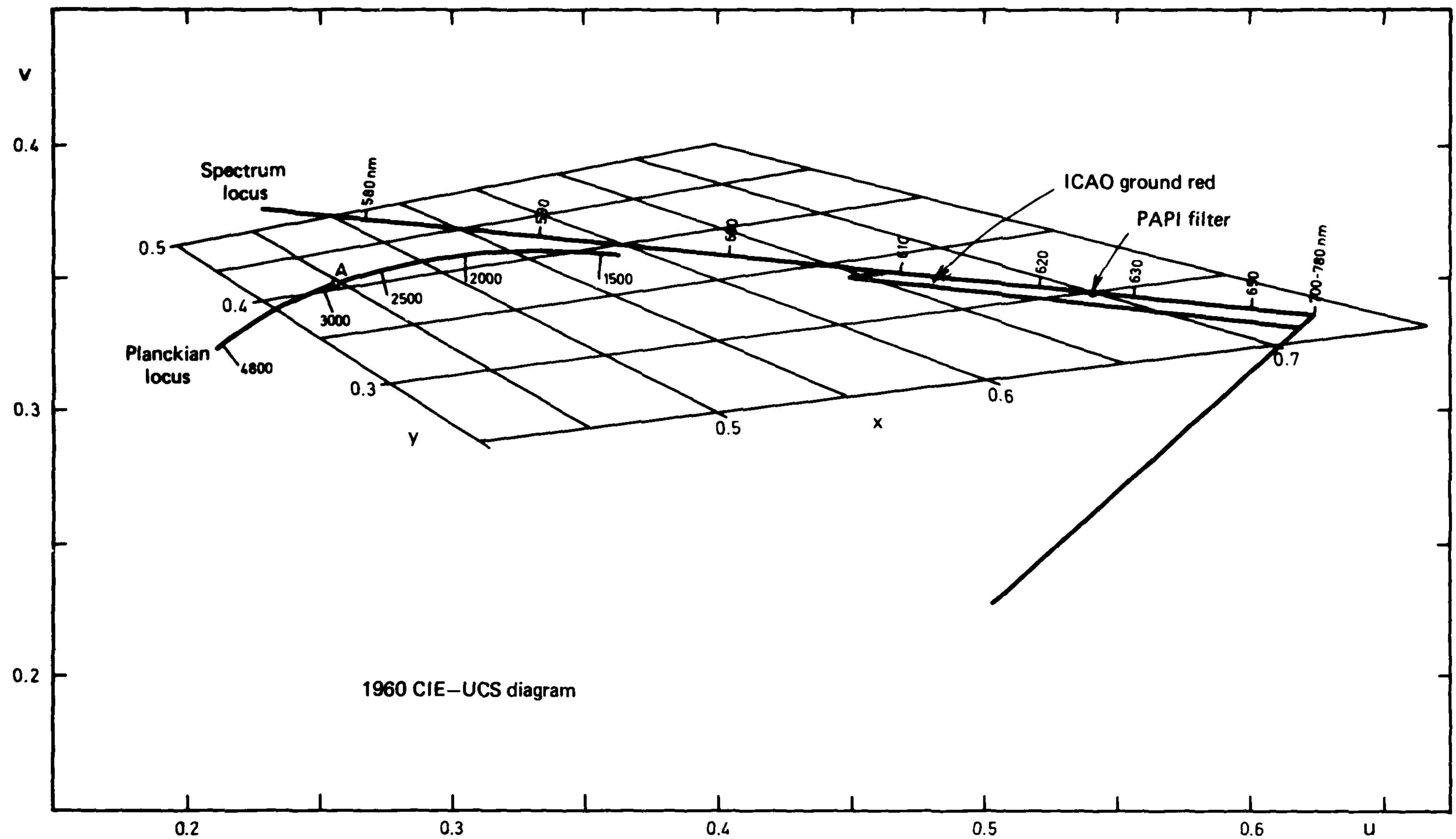

Fig. 1 Part of the 1960 CIE–UCS diagram showing the transformed x, y grid, the Planckian locus with colour temperatures in degrees K, the boundary for ICAO red aeronautical ground lighting, and the position of the PAPI filter.

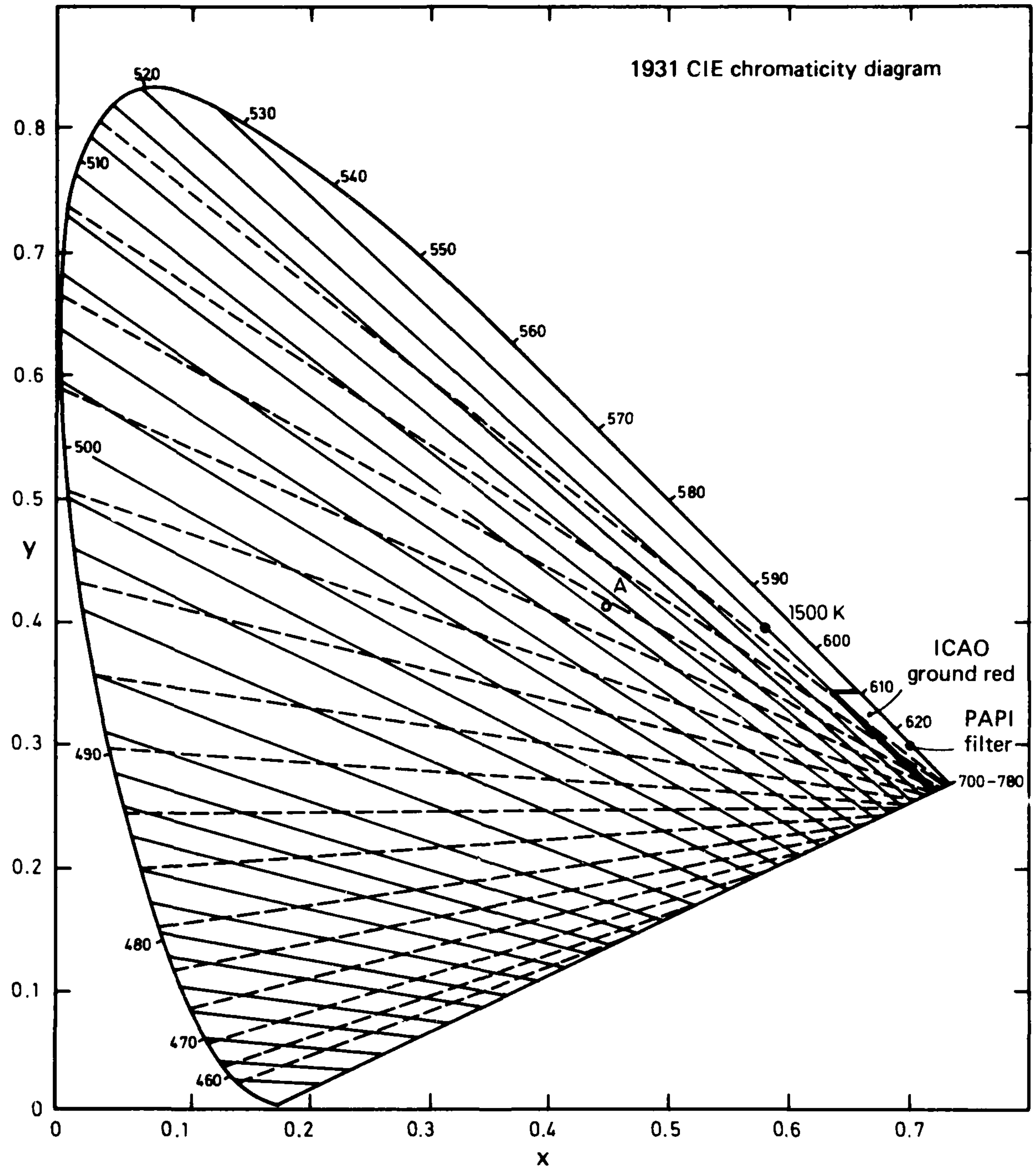

Fig. 2 Confusion loci for protans (broken lines) and deutans (solid lines) on the 1931 CIE chromaticity diagram. CIE Illuminant A, a 1500 K light source, the boundary for ICAO red aeronautical ground lighting, and the PAPI filter are also shown.

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