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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, ***Secretary***
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

The U.S. committment to a voluntary conversion to metric units raises changeover problems in the fields of air traffic control and airspace management. This report begins by discussing current practice in altitude measurement and the rules for height maintenance now in effect worldwide. Four desirable features are given for an altitude measurement system, encompassing both the units of height measurement and the designation of cruising levels. Three alternative bases for the design of such a system are discussed and related to the desirable characteristics. Problems associated with each of the approaches are discussed and the many factors to be considered and the many interrelationships involved are examined.

Key Words: Altimetry; altitude; aviation; height measurement; measurement units; metric; standardization; vertical separation.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

On December 23, 1975 President Ford signed into law PL 94-168, the Metric Conversion Act of 1975, which authorized the appointment of a 17-member U.S. Metric Board to coordinate a voluntary changeover to the metric system. Metric units have been legal in the U.S. since 1866, but have not been in general use. In the last 25 years, the metric system has become the dominant language of measurement in the world. Only the United States, among the more developed nations, has not adopted its use officially. The Metric Conversion Act of 1975 emphasized the country's determination eventually to adopt metric units for most applications, particularly in areas having international impact. One such area is the regulation of international air traffic.

The basic metric units, from which all others are derived, are six [6]:

length - meter
mass - kilogram
time - second
electric current - ampere
thermodynamic temperature - degree Kelvin
luminous intensity - candela

One of the units derived from these is the metric unit of pressure, the Pascal (Pa), measured in Newtons per square meter: in basic units, $m^{-1} \cdot kg \cdot s^{-2}$. In addition to the basic metric units and those derived from them, the International Committee of Weights and Measures (CIPM) recommended [6] in 1969 the retention, for the time being, of several other units including the nautical mile, the knot, the bar (1 bar = 10^5 Pa) and the standard atmosphere (1 atm = 101,325 Pa).

In the U.S., aircraft altitude is currently expressed either in feet or in hundreds of feet. The actual measurement process is more complicated than this and will be described below, but the units of measurement in which altitude is expressed are length units. Conversion to the metric system will require either transformation to metric length units (meters), or the choice of an alternate physical quantity to express altitude.

The purpose of this paper is to explore the problems associated with metrication of altitude measurement. Solution of these problems is difficult, perhaps involving equipment modification and changing human orientations in a safety-critical environment. In fact, the U.S. Metric Study Report A Metric America - A Decision Whose Time Has Come [2, p. 129] noted:

> 'There is unlikely to be any early change in air navigation practices, particularly in units used for air-to-ground communications in traffic control or for the calibration of flight instruments. International civil aviation uses two differnet sets of standards; both include the knot and nautical mile, but one set measures speed and vertical distances in kilometers per hour and meters, the other in miles per hour and feet.'

The slowness of the world aviation community in changing over to metric units results in part from U.S. dominance in this field. The Metric Study Report [2, p. 131] notes in this vein that aircraft manufacturers in Great Britian

> 'agreed to make every effort to comply with the Defence Ministry's program. But they pointed out that unless the U.S., the world's largest manufacturer and operator of civil aircraft, changes over to metric, two sets of units are likely to be current for some time to come.'

With the U.S. committed to metric conversion, albeit a voluntary conversion, it is appropriate to consider change in the measurement units of worldwide aviation. Metric countries are already actively seeking such a conversion (see for example [8]).

If the U.S. is to take an active role in the design and promulgation of metric regulations in aviation, it must conduct its own study and analysis of the various approaches and must assess impacts on the domestic aviation community. This report is designed to assist in that task, by presenting criteria for the units of height measurement and by identifying problems associated with several plausible approaches.

2. EXECUTIVE SUMMARY AND CONCLUSIONS

The enactment of the "Metric Conversion Act of 1975" (PL 94-168) has made examination of the units of altitude measurement appropriate at this time. The discussion in this document addresses the problems associated with three possible approaches to revising the present system of units. The impact of these changes on avionics and ground equipment as well as the pilot, controller and operating procedures make it clear that a selection of a satisfactory system of units will be difficult.

The three alternatives evaluated were:

1. use of the present flight level system without direct reference to feet,
2. measurement of altitude in meters and use of a metric flight level system,
3. use of some function of the pressure measurement itself, rather than its linear transform.

The suggested criteria for a new system of units were also delineated. None of the three approaches reviewed meet all four of the criteria which where that:

1. the units used for expressing altitude should be a linear function of height,
2. flight levels should be equally spaced or at intervals which are small multiples of some basic spacing,
3. flight-level units should have as few digits as possible,
4. all altitude references should be based on the same units.

The selection of a new system of units will be complex task involving trade-off study of the many factors involved. A most difficult area will be the evaluation of the effect of changing human orientations in a safety-critical environment. A conversion of the altitude measurement system to metric units is not practical in the near future.

3. CURRENT HEIGHT-MEASUREMENT REGULATIONS AND PRACTICE

Current International Civil Aviation Organization (ICAO) regulations related to altitude maintenance are given in [1]:*

> 5.2 Rules applicable to IFR flights within controlled airspace
>
> 5.2.2 An IFR flight operating in cruising flight in controlled airspace shall be flown at a cruising level, or, if authorized to employ cruise climb techniques, between two levels or above a level, selected from:
>
> a) the Table of cruising levels in Appendix C, or
>
> b) a modified table of cruising levels, when so prescribed in accordance with Appendix C for flight above flight level 290,
>
> except that the correlation of levels to track prescribed therein shall not apply whenever otherwise indicated in air traffic control clearances or specified by the appropriate ATS authority in Aeronautical Information Publications.
>
> 5.3 Rules applicable to IFR flights outside controlled airspace
>
> 5.3.1 Cruising Levels - An IFR flight operating in level cruising flight outside of controlled airspace shall be flown at a cruising level appropriate to its track as specified in:

---

*The terms IFR, VFR and ATS authority appearing here are defined below:

IFR: Instrument Flight Rules. Under poor visibility conditions or in certain airspace aircraft must fly according to instrument flight rules. In addition, many aircraft, especially air carrier craft, usually fly IFR in contact with an air traffic controller.

VFR: Visual Flight Rules. Aircraft may fly using these procedures when visibility is acceptably clear at lower altitudes.

ATS: Air Traffic Services. This is used to refer to the formally designated appropriate air traffic control authority.

a) the Table of cruising levels in Appendix C, except when otherwise specified by the appropriate ATS authority for flight at or below 900 metres (3000 feet) above mean sea level; or

b) a modified table of cruising levels, when so prescribed in accordance with Appendix C for flight above flight level 290.

4.3 Unless authorized by the appropriate ATS authority, VFR flights shall not be operated:

a) between sunset and sunrise, or such other period between sunset and sunrise as may be prescribed by the appropriate ATS authority;

b) above flight level 200;

c) at transonic and supersonic speeds

4.5 Except as provided in 4.5.1, VFR flights in level cruising flight when operated above 900 metres (3000 feet) from the ground or water, or a higher datum as specified by the appropriate ATS authority, shall be conducted at a flight level appropriate to the track as specified in the Table of cruising levles in Appendix C.

4.5.1 VFR flights operated in controlled airspace (instrument/visual) shall select cruising levels from those to be used by IFR flights as specified in 5.2.2, except that the correlation of levels to track shall not apply whenever otherwise indicated in air traffic control clearances or specified by the appropriate ATS authroity in Aeronautical Information Publications.

The table of cruising levels from Appendix C of [1] is reproduced as Figure 1. The definitions of "cruising level" and "flight level" (FL) from [1] are given below:*

---

*The terms QNH and QFE used in Note 1 refer to the process used in calculating altitude. A QNH setting (NH stands for natural height) utilizes the sea level barometric pressure for the local area in which the aircraft is operating and results in a height measurement closely approximating actual distance above sea level. A QFE setting uses the standard atmosphere everywhere and represents an approximate height measurement for which the degree of approximation depends on the difference between the actual and assumed sea level barometric pressure.

FIGURE 1

ICAO-Recommended Cruising Levels

APPENDIX C.—TABLE OF CRUISING LEVELS

The cruising levels to be observed when so required by this Annex are as follows:*

TRACK**											
From 000° *to* 179°***						*From* 180° *to* 359°***					
IFR Flights			VFR Flights			IFR Flights			VFR Flights		
FL	Altitude		FL	Altitude		FL	Altitude		FL	Altitude	
	Metres	*Feet*		*Metres*	*Feet*		*Metres*	*Feet*		*Metres*	*Feet*
-90			—	—	—	0			—	—	—
10	300	1 000	—	—	—	20	600	2 000	—	—	—
30	900	3 000	35	1 050	3 500	40	1 200	4 000	45	1 350	4 500
50	1 500	5 000	55	1 700	5 500	60	1 850	6 000	65	2 000	6 500
70	2 150	7 000	75	2 300	7 500	80	2 450	8 000	85	2 600	8 500
90	2 750	9 000	95	2 900	9 500	100	3 050	10 000	105	3 200	10 500
110	3 350	11 000	115	3 500	11 500	120	3 650	12 000	125	3 800	12 500
130	3 950	13 000	135	4 100	13 500	140	4 250	14 000	145	4 400	14 500
150	4 550	15 000	155	4 700	15 500	160	4 900	16 000	165	5 050	16 500
170	5 200	17 000	175	5 350	17 500	180	5 500	18 000	185	5 650	18 500
190	5 800	19 000	195	5 950	19 500	200	6 100	20 000	205	6 250	20 500
210	6 400	21 000	215	6 550	21 500	220	6 700	22 000	225	6 850	22 500
230	7 000	23 000	235	7 150	23 500	240	7 300	24 000	245	7 450	24 500
250	7 600	25 000	255	7 750	25 500	260	7 900	26 000	265	8 100	26 500
270	8 250	27 000	275	8 400	27 500	280	8 550	28 000	285	8 700	28 500
290	8 850	29 000	300	9 150	30 000	310	9 450	31 000	320	9 750	32 000
330	10 050	33 000	340	10 350	34 000	350	10 650	35 000	360	10 950	36 000
370	11 300	37 000	380	11 600	38 000	390	11 900	39 000	400	12 200	40 000
410	12 500	41 000	420	12 800	42 000	430	13 100	43 000	440	13 400	44 000
450	13 700	45 000	460	14 000	46 000	470	14 350	47 000	480	14 650	48 000
490	14 950	49 000	500	15 250	50 000	510	15 550	51 000	520	15 850	52 000
etc.	*etc.*	*etc.*	*etc.*	*etc.*	*etc.*	*etc.*	*etc.*	*etc.*	*etc.*	*etc.*	*etc.*

* *Except when, on the basis of regional air navigation agreements, a modified table of cruising levels based on a nominal vertical separation minimum of less than 600 metres (2 000 feet) but not less than 300 metres (1 000 feet) is prescribed for use, under specified conditions, by aircraft operating above flight level 290 within designated portions of the airspace.*

** *Magnetic track, or in polar areas at latitudes higher than 70° and within such extensions to those areas as may be prescribed by the appropriate ATS authorities, grid tracks as determined by a network of lines parallel to the Greenwich Meridian superimposed on a polar stereographic chart in which the direction towards the North Pole is employed as the Grid North.*

*** *Except where, on the basis of regional air navigation agreements, from 090° to 269° and from 270° to 089° is prescribed to accommodate predominant traffic directions and appropriate transition procedures to be associated therewith are specified.*

Cruising level. A level maintained during a significant portion of a flight.

Flight levels. Surfaces of constant atmospheric pressure which are related to a specific pressure datum, 1013.2 mb (29.92 inches), and are separated by specific pressure intervals.

Note 1 A pressure type altimeter calibrated in accordance with the Standard Atmosphere:

a) when set to a QNH altimeter setting, will indicate altitude;

b) when set to QFE altimeter setting, will indicate height above the QFE reference datum;

c) when set to a pressure of 1013.2 mb (29.92 inches), may be used to indicate flight levels.

Note 2 The terms height and altitude used in Note 1 above, indicate altimetric rather than geometric heights and altitudes.

Altimeters do not determine height directly by a length ("geometric") measurement. Rather, an altimeter measures a pressure difference, between the ambient air pressure outside the aircraft and some sea-level reference atmospheric pressure. If the aircraft is flying at a lower altitude (below FL180 in the U.S.), the reference pressure will be sea-level barometric pressure supplied by local weather stations. For altitudes at and above FL180, the reference pressure used is the standard atmosphere, 1013.25 millibars or 29.92 inches of mercury, the millibar definition being the one preferred by ICAO.

The altimeter instrument translates the pressure difference to an ('altimetric') height above sea level. This height would be actual geometric height if the reference barometric pressure were the true sea-level barometric pressure at that point, and if the ambient air conditions (temperature and density) happened to equal exactly the ideal conditions used in the equation of transformation from pressure differences to height. Since these special circumstances will in general not obtain, the pressure altitude calculated by the altimeter will differ from true geometric height. However, as long as they use the same reference barometric pressure, altimeters in all aircraft should measure the same pressure altitude, and differences between adjacent flight levels should approximate the true geometric height differences.

The table in Figure 1 lists the pressure altitudes in both feet and meters for the cruising levels which are to be used by all flights. Note that while meters and feet are given equal status (with meters even listed first), the flight-level designations are actually the altitudes expressed in hundreds of feet. Thus the ICAO-supported altitude designations of cruising levels are implicitly based on the customary, rather than metric, units.

Separation between adjacent IFR levels is an even 1000 feet below FL290 and an even 2000 feet above FL290, where adjacent levels on the same track carry traffic in opposite directions. (Compare entries on the same line in the two "IFR Flights" columns of Figure 1.) The difference, in meters, between adjacent IFR levels below FL290 is generally 300 meters but sometimes is 350 meters. Above FL290 the metric difference is usually 600 but occasionally may be 650. This variation in the metric flight level makes them much more difficult to remember and use. In fact, the controllers and pilots generally refer only to the cruising-level designation, not to the equivalent height. Altimeters in most aircraft, except those of the Soviet Union and Eastern Europe, use feet so that the pilot can use the altimeter reading directly in communicating with the controller about altitude. Thus the current practice in use throughout the world, outside of Eastern Europe and the Soviet Union, involves the use of nonmetric altitude designations.

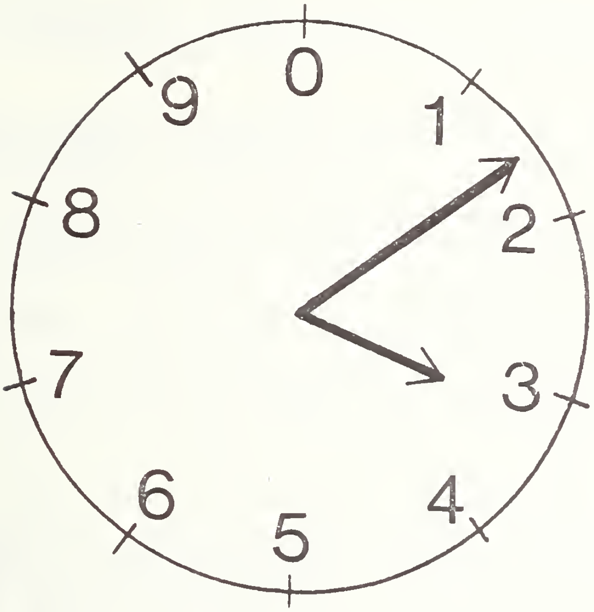
Figure 2 shows two types of altimeter displays. One, a clock-type which is the most common, has a short hand indicating the coarse altitude reading (1000's of feet) and a long hand indicating the fine altitude reading (100's of feet). The second, which is becoming more common, gives the coarse reading in a digital odometer-type display and the fine reading by a pointer indicating 100's of feet. Other altimeter displays exist (for examples see [9]), but these two are the most common types in use today. Both types of display also show the reference barometric pressure on the face.

Because of the number of dials and guages in the cockpit, the pilot cannot consult each in detail at every glance. Rather, he carefully scans the few of the instruments most appropriate during any maneuver, and only glances at the others for deviation from expected position. To ease this process, the instrument displays (including that of the altimeter) are designed so that pointers will be in a vertical position (i.e. "pointing up") when the instrument recording is the desired value. Thus when the pilot is exactly at one of the cruising levels given in Figure 1 (for IFR traffic), his altimeter fine pointer will be straight up, if he has either of the two displays in Figure 2. During climb or descent the pilot will consult both coarse and fine altimeter readings to insure correct altitude is attained, but during level flight he need only maintain the fine pointer in a vertical position.

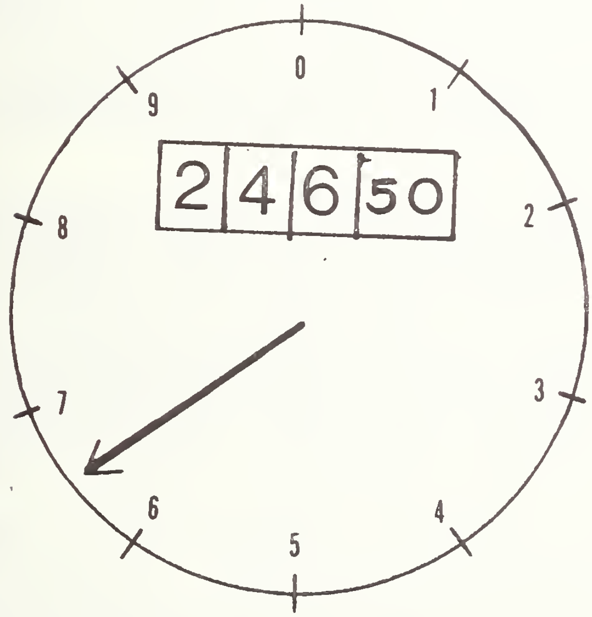
Altitude information is relayed to controllers on the ground by the airborne Mode C transponder. This instrument, when triggered by a radio signal, sends a 3-digit altitude code which is received at the point which sent the triggering signal. Most aircraft in upper altitudes or in high-density IFR terminal areas are equipped with transponders with Mode C

FIGURE 2

Examples of Common Altimeter Displays



Clock-type Display



Counter-Pointer Display

capability. Equipment associated with the radar processes the signal, and the 3-digit altitude code is included in an alpha-numeric display on the radar scope of the controller who is handling this aircraft. The transponder encodes and transmits only the 3-digit coarse altitude reading rounded and smoothed to eliminate frequent changes in the last digit when an aircraft is in between two hundred foot levels.

In the U.S., or any other place in which the coarse 3-digit reading is the altitude in hundreds of feet, the controller can consult the rightmost of the three digits. If it is 0, the pilot is exactly on one of the cruising levels (below FL290). Otherwise, the last digit indicates how far in error the pilot is. Above FL290 the controller must also consult the second digit to determine that it is odd, in ascertaining whether the aircraft is at an appropriate flight level. Thus for altimeters reading in feet, the 3-digit Mode C altitude can be used by the controller both as a positive indication that the aircraft is maintaining correct altitude, and if not, as an indication of the magnitude of the deviation.

The controller is not required to monitor constantly the Mode C altitude displayed on his scope. Rather, keeping track of the appropriate altitude is an advisory service provided on an 'as available' basis. However, if a U.S. controller does notice a discrepancy of more than 300 feet between assigned altitude and Mode C displayed altitude, he must check with the pilot to ascertain whether the cockpit altimeter agrees with the Mode C response (and the aircraft has indeed wandered from its correct cruising level) or the discrepancy is one between the cockpit altimeter and Mode C. In the latter case, the cockpit reading is assumed correct, and the pilot is requested to turn off Mode C. This check is usually done, where necessary, at handoff from one sector to another. Therefore, although checking of altitude by controllers is not a required activity, the procedures assure that it is usually done at least at handoff. In addition, the structure of the altitude display code (which makes recognition of altitude deviation easy) aids continuous monitoring.

It is clear, from this description of current practice, that changeover to metric altitude reporting would require more than just redesigning altimeter dials, adding a second set of units on the dial or overlaying current units with metric values. Some consideration must be given to changing the cruising-level structure, perhaps to represent constant metric differences. Changed cruising levels must be coordinated with vertical separation standards to assure that any reduction in separation resulting from the change is safe. Changes in the units of altitude measurement will also have an impact on Mode C transponder encoding, and on the display of the Mode C altitude upon the controller's radar scope. In addition, other altitude references in charts and handbooks must be changed to ensure compatiability. All references to altitude, whatever the source or application, must be expressed in the same units. In the remainder of this report we will use the term 'altitude measurement system' to denote the system elements involving altitude units and the interactions among them. This includes the units used to express altitude, the scheme of assigned flight levels, and the relationships among the units used by the various instruments, such as altimeter, Mode C transponder and controller radar display.

4. DESIRABLE CHARACTERISTICS OF AN ALTITUDE MEASUREMENT SYSTEM

From the preceding discussion of the current regulations applying to altitude and the accompanying description of operational aspects of the altitude maintenance system, several desired characteristics arise:

1. It is desirable that the units used for expressing altitude be a linear function of height.

2. Flight levels should be equally spaced, or at intervals which are small multiples (i.e., by 2 or 3) of some basic spacing.

3. Flight-level units should have as few digits as possible.

4. All altitude references should be based on the same units.

Further elaboration and justification of these criteria will be given below, in the respective Sections 4.1 through 4.4.

The Military Standard - Human Engineering Design Criteria for Military Systems, Equipment and Facilities [5] contains specifications for visual displays, such as the pilot's altimeter gauge or the controller's radar scope. These specifications are relevant to the units used and how they are to appear on such a display. General requirements concerning the information to be displayed include [5, p. 25]

> Content - The information displayed to an operator shall be limited to that which is necessary to perform specific actions or to make decisions.
>
> Precision - Information shall be displayed only to the degree of specificity and precision required for a specific operator action or decision.
>
> Format - Information shall be presented to the operator in a directly usable form. (Requirements for transposing, computing, interpolating, or mental translation into other units shall be avoided.)

The same document recommends that coding techniques be used, among other things, to identify critical information within a display. The four criteria enunciated above apply these general principles, together with other well-recognized desirable characteristics, to the problem of altitude measurement.

4.1 Linear Scale

It is generally believed that people understand linear units and can read linear displays much more easily than others. The Military Standard [5, p. 35] recommends, for instance, that

> 'Except where system requirements clearly dictate nonlinearity to satisfy operator information requirements, linear scales shall be used in preference to nonlinear scales.'

In addition to the general desirability of linear scales, a specific reason for requiring altitude units to be a linear function of height is that climb and descent rates are usually expressed in vertical units per time period (feet or meters per second or minute). If a non-linear function of height were used, climb and descent rates would depend on the altitude, and the time to fly from one flight level to the next would also vary. This would be confusing for pilots and would impose an additional mental burden, involving translation or calculation, in an environment sometimes requiring split-second decisions.

Non-linear units would also violate the second criterion enunciated above. Separation between flight levels should either be constant, or should only involve low multiples of the base separation; units which were a nonlinear function of height would probably lead to non-constant separation intervals (when the intervals were expressed in those nonlinear vertical units). This again would put upon the pilot and the controller the great burden of retaining mentally the expanded information-base required by such a system.

4.2 Equally Spaced Flight Levels

The second and third criteria relate the units of altitude measurement to the specification of cruising levels (as in the table of Figure 1). Although aircraft can fly at any altitude (within their performance range), pilots are requested -- either by rules such as the ICAO regulations quoted in Section 2, or by controller instructions -- to fly at one of the specified cruising levels when in level flight. Even ascent and descent are often accomplished in stages, chosen to alternate a priod of altitude change with a period of level flight at one of the cruising levels.

Equal spacing between cruising levels makes the levels easier to remember and easier to use during climb or descent, for reasons similar to those for use of a linear scale. The equal-spacing requirement is in part a response to the need for the simplest design compatible with functional specifications. In this vein the Military Standard [5, pp. 15 and 17] notes that

> 'Design shall also be directed toward minimizing personnel and training requirements within the limits of time, cost, and performance trade-offs.'
>
> 'The equipment shall represent the simplest design consistent with functional requirements and expected service conditions.'

Another justification for using flight-levels which are equally spaced, or based on multiples of a basic separation, is found in the cockpit procedures used by pilots to monitor their instruments: they fly "pointers up". This also is in accordance with the Military Standard for human factors design of instruments which states [5, pp. 38-39]:

> Zero Position and Direction of Movement - When positive and negative values are displayed around a zero or a null position the zero or null point shall be located at either 12 o'clock or the 9 o'clock position. Positive values shall increase with clockwise movement of the pointer, and negative values shall increase with counterclockwise movement.
>
> Alignment of Pointer or Fixed Reference Line - Alignment of pointer or fixed reference line shall be in the 12 o'clock position for right-left directional information and in the 9 o'clock position for up-down information. For purely quantitative information, either position may be used.
>
> Pointer Alignment - When a stable value exists for given operating conditions in a group of circular-scale indicators, they shall be arranged either in rows so that all pointers line up horizontally on the 9 o'clock position under normal operating conditions or in columns so that all pointers line up vertically in the 12 o'clock position under normal operating conditions. If a matrix of indicators is needed, preference shall be given to the 9 o'clock position.

If each complete rotation of the pointer corresponds to the same number of units, then having each cruising level represented by a 12 o'clock position requires that the cruising levels be separated by multiples of the number of units in one complete pointer sweep.

In summary: for reasons of simplicity and compatibility with cockpit procedures, equally-spaced cruising levels are desirable.

4.3 Few Digits

As noted under the heading of simplicity, the Military Standard requires that the information displayed be the minimum needed to meet functional requirements. Current cruising-level designations require only two digits, with a third used to indicate deviations. Metric levels based on the values in Figure 1, or based on a fixed 300/600 meter separation, would require 3 digits since successive levels may have different third digits. Deviation from level would thus become more difficult to spot. In addition, it is intuitively clear that requiring three digits rather than two, places an additional burden of memory and recognition and communication on both pilot and controller. This intuitive idea is reinforced by a study [7] conducted by the National Bureau of Standards for the U.S. Postal Service in which operators were found to require 0.89 seconds on the average to recognize two digits of a Zip-code, but 1.17 seconds to recognize 3 digits. (This difference was statistically significant at the .0005 level.)

It is clear that a cruising-level system should have designations with as few digits as possible. Also, as will be discussed in Subsection 3.4, all references should use the same units. That is, the system should not use one set of units for display on a controller's scope or for assigned flight levels, and a second set on cockpit instruments.

Another principle stated in the Military Standard [5, p. 30] which is applicable to the use of the cruising-level designations is:

> Positive Feedback - The absence or extinguishment of a signal or visual indication shall not be used to denote a "go-ahead", "ready", "in-tolerance", or completion condition, nor shall such absence be used to denote a "malfunction", "no-go", or "out-of-tolerance" condition.

In the current cruising-level system, the third digit is always zero. Therefore, a non-zero value for that digit on the controller's display indicates a deviation, and the value of the digit indicates the magnitude of the deviation. This makes it fairly easy for the controller to scan his display for altitude errors. The third digit therefore satisfies the principle stated above. In the case of a metric curising-level system, the value of the third digit by itself does not provide a positive feedback. It must be combined with the two preceding digits, and the whole triple examined to obtain the same information as that provided by the third digit alone in the current system.

In summary: the current cruising-level system is particularly well-designed to exploit the greatest information in the fewest digits, giving both a positive indication of "on assigned level" and a positive indication of deviation and its magnitude. Loss of these advantageous features would be a serious matter.

4.4 Single System of Units

This requirement seems particulary straightforward for any safety-critical application like aviation, in which communication between various system elements is a major factor. Pilots use their altimeters in responding to requests from controllers. The controllers assign pilots to altitudes and use displayed Mode C responses to monitor actual altitude. Handbooks listing airport heights are used by pilots in checking the altimeter instrument readings. Charts list minimum safe altitudes and heights of possible obstructions. "Altitudes" appearing in all these contexts must be in the same units. Other aspects of altitude usage which must be considered include units of climb and descent, the cruising-level system and vertical separation standards. The units chosen for altitude measurement will limit choice of separation values, which in turn will determine cruising levels. All must then be coordianted to meet criteria 1-3 (see the beginning of this Section) as well as criterion 4.

Our discussion of these four criteria has exhibited the complexity of the factors which must be considered in choosing units. It has also served to show the many inter-relationships involved in the use of altitude units. New units should not be such as to rule out or hobble any of the current uses, and should neither degrade the quality of information now available nor increase the quantity required. These constraints are particularly difficult to satisfy if metric units are to be employed and if current separation values (whose magnitudes are determined independently of the length units used) are to be retained.

5. DISCUSSION OF ALTERNATIVES

Sections 2 and 3 have described the current regulations and operating procedures affecting altitude measurement and maintenance, and have presented criteria for the design of a system for altitude measurement and cruising levels. In this section we will examine three alternative approaches to such a system:

1. Use the present flight-level system without direct reference to feet.

2. Measure altitude in meters and use a metric flight-level system.

3. Use some function of the pressure measurement itself, rather than its linear transform. (This is suggested in [3].)

We will discuss the advantages and disadvantages of each approach, relating these to the criteria given in Section 4.

5.1 Present Flight Levels

Because of variations in local barometric pressure and deviations from the ideal conditions relating pressure and altitude, it is only by pure chance that any aircraft would actually be flying at the geometric height indicated by its altimeter. It has therefore been suggested that the current altimeter readings in feet should be replaced. Instead, altitude would be measured in artificial units called (perhaps) "flight levels", and in fractions thereof. An altimeter reading of 27315 would be read as 273.15 flight levels, for instance. This approach has the advantage of retaining all the desirable characteristics of the current system: its linearity, equal spacing, and especially the use of fewest digits to express the information. The main advantage of this approach is the economy with which it expresses the actual altitude, an indicator of "on flight level" and an indication of the magnitude of any deviation, all within three digits.

There are serious disadvantages, however. The U.S. is committed to the eventual adoption of metric units, with exceptions where necessary. Divorcing "flight level" from "feet" does not change the fact that "flight level" is not a metric unit. It would seem particularly strange for such a high-technology industry as aviation to retain archaic non-metric units.

An even more serious problem is that use of flight level would perpetuate a dual system of units, with Eastern Europe and the USSR using meters and others using the new flight-level units. The increasing pressure from metric countries to use meters (see for example [8]) could result in even more countries using meters, again leaving the U.S. "odd man out". The use of non-metric units, however disguised, is contrary to the intent of the Metric Conversion Act.

5.2 Metric Units

Perhaps the most direct approach to world-wide standard altitude measurement is to use the metric unit of length as the unit of altitude, and to define flight level in terms of multiples of some basic number of meters. The table in Figure 1 displays metric equivalents for levels which are based on increments expressed primarily in feet. An alternative table, with increments based on 300 and 600-meter steps, would be more appropriate. Such a table is displayed in Figure 3. The flight-level designations used are 10's of meters, so that the final digit has the desirable characteristics of positive feedback of "on-level" indication, and of estimation of deviation-from-level using the final digit. The first 3 or 4 digits also agree with the altimeter reading, so no translation would be required.

The main disadvantage of such a system is that it requires more digits (4 rather than 3) to convey the same amount of information as does the current feet-based flight level system. In addition, whereas the leading digits in the current system progress in increments of 1 or 2, those of the flight level system in Figure 3 progress in increments of 3 or 6, violating an additional principle stated in the Military Standard [5, p. 35], namely:

> Graduations - Scale graduations shall progress by 1, 2, or 5 units or decimal multiples thereof.

The progression by 3 or 6 is clearly more difficult to remember, placing an additional burden on both pilot and controller.

The extra digits required by a metric flight-level system would require redesign of Mode C transponders and of the on-ground equipment which processes the transponder digital signal: the additional digit would require a lengthening of the transmission interval, as well as additional altitude codes. The controller's display would also be affected by the need to include the additional digit. Aircraft owners would thus incur a cost for equipment purchase or modification, and the FAA would incur design, development and hardware costs associated with the changeover. Other costs would result from altimeter modification (the metric altimeter for such a system would probably have a fine pointer rotating every 300 meters and would utilize a digital display for the coarse measurement). New charts and handbooks would have to be preapred, published, and pruchased.

Many of these costs are similar to those incurred in metric changeover by other industries. Whether they are warranted in the present case depends on the degree to which the aviation community, here and internationally, is committed to metric units. Should other countries make the changeover, the U.S. aviation industry, the acknowledged world leader, could ill-afford to remain aloof and isolated.

If a decision is made to proceed to metric altitude units, then the changeover process must be analyzed and planned with great care. Gradual changeover presents the difficulties resulting from having both systems concurrently in use, with dual communication putting an intolerable burden on controller and pilot. Having dual flight-level systems in concurrent use would be confusing and would decrease safety by having a mix of aircraft following different levels.

FIGURE 3

Metric IFR Flight Level System

From 000° to 179°			From 180° to 359°		
FL	Altitude		FL	Altitude	
	Meters	Feet		Meters	Feet
30	300	990	60	600	1980
90	900	2970	120	1200	3960
150	1500	4950	180	1800	5940
210	2100	6930	240	2400	7920
270	2700	8910	300	3000	9900
330	3300	10890	360	3600	11880
390	3900	12870	420	4200	13860
450	4500	14850	480	4800	15840
510	5100	16830	540	5400	17820
570	5700	18810	600	6000	19800
630	6300	20790	660	6600	21780
690	6900	22770	720	7200	23760
750	7500	24750	780	7800	25740
810	8100	26730	840	8400	27720
870	8700	28710	930	9300	30690
990	9900	32670	1050	10500	34650
1110	11100	36630	1170	11700	38610
1230	12300	40590	1290	12900	42570
1350	13500	44550	1410	14100	46530
1470	14700	48510	1530	15300	50490
etc.	etc.	etc.	etc.	etc.	etc.

An abrupt changeover in a safety-critical environment can proceed smoothly, as evidenced by the Swedish switch from left to right drive on the highway. However, the Swedish example did not involve simultaneous modification of equipment. An abrupt changeover would necessitate an interval of dual systems in the cockpit, since equipment installation requires time. This might be difficult in aircraft whose control panels are already crowded with instruments.

This discussion has been included to point out some of the problems implicit in a changeover to metric altitude units. It should not be construed as implying that we see no possibility of solving these problems, but does serve to emphasize that such a decision should reflect careful study of the whole system of altitude measurement and maintenance.

5.3 A Function of Pressure

Since altitude is not calculated directly as a length, it is natural to suggest that the units of altitude reflect more directly the measurement being made. This has led Du Feu, for instance, to suggest in [3] an alternative unit system based directly on ambient air pressure at altitude. He suggests that the units y to be used to measure altitude be expressed as

$$y = y_0 + kP^x$$

where P is the measured pressure and k and x are parameters chosen in such a manner as to assure that appropriate minimum separations between flight levels are maintained. In [3] he obtains values of

$$y = y_0 - 1.39P^{0.57597} \qquad (1)$$

for values below 11 km (36,089 feet). The value of y_0 is chosen to make $y=0$ at sea level (where $P=1013.25$ mbar). Equation (1) is based on separation values suggested by IATA, which are less than those currently used. Flight levels would be 1 unit of y (which Du Feu calls a Cayley) apart.

This system has the advantage of relating directly to the pressure measurement being performed, and the variable separation interval reflects measurement accuracy more directly than does the linearized altitude now used. However, this approach violates criterion 1 of the previous section, since Cayleys are not a linear function of height. It is true that the units would appear on a linear scale in the cockpit, and that separation between flight levels, when measured in Cayleys, is constant. However, climb and descent rates will vary with altitude, and time to travel between flight levels will be difficult to estimate. Thus this approach would put an additional burden on pilots requiring retraining and familiarization with a new system. The particular flight level system derived in [3] is undesirable because of the reduced separation involved, but this alone is not reason to reject the underlying approach. The main difficulty is still the non-linearity with height, and the resultant requirement for modifications in flying practice. This approach would also require redesign of the airborne altimeter system.

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The U.S. committment to a voluntary conversion to metric units raises changeover problems in the fields of air traffic control and airspace management. This report begins by discussing current practice in altitude measurement and the rules for height maintenance now in effect worldwide. Four desirable features are given for an altitude measurement system, encompassing both the units of height measurement and the designation of cruising levels. Three alternative bases for the design of such a system are discussed and related to the desirable characteristics. Problems associated with each of the approaches are discussed and the many factors to be considered and the many interrelationships involved are examined.

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