Dynamic Non-Linear Displays - Principles and Practice

Dr. John Maris[1], Finlay Wynd Smith[2]
Cert Center Canada
Saint-Bruno, QC, J3V 2A5, Canada
john.maris@certcentercanada.com; finlay.wyndsmith@certcentercanada.com

Dynamic Non-Linear Displays (DNLD) were developed to reconcile the mutually conflicting demands affecting EFIS and HUD tape displays for dynamic legibility, wide scale range, and adequate precision. For example, traditional tape altimeters typically limit their analog displayed range to ±300 ft in order to maintain the necessary 20 ft resolution.

TRL-7 flight evaluations have shown that DNLD satisfies all three display requirements, while maintaining full scale linearity in the fine-control region. DNLD displays exhibited no discontinuities, remained legible at extreme aircraft rates, and never went out of range (so DNLD altimeters, for example, always kept the underlying terrain elevation in view). Finally, DNLD constantly presented the entire range of feasible values (such as all 360˚ of a compass) for each displayed parameter. Because of these characteristics, and unlike conventional displays, DNLD can contribute to all three levels of Situational Awareness identified by Endsley: perception, comprehension, and prediction of the displayed parameter.

DNLD has been successfully trialed by Canada's National Research Council, and is ready for additional flight and simulator testing to further evaluate and refine the DNLD concept. Potential applications for DNLD include HUDs and Electronic Standby Instrument Systems.

1. INTRODUCTION

1.1. Abbreviations and symbols

The following abbreviations and symbols are introduced in this paper.

Table 1. Abbreviations and symbols.

Symbol	Meaning
$B_L(t)$	Bézier display value in parametric form
DNLD	Dynamic Non-Linear Display
EFIS	Electronic Flight Instrument System
EPA	DNLD non-linear zone end-point anchors
EPA_L	DNLD non-linear zone lower end-point anchor
EPA_U	DNLD non-linear zone upper end-point anchor

[1] SFTE Member
[2] SFTE Student Member

Symbol	Meaning
HUD	Head Up Display
LZ_L	Lower limit of DNLD Linear Zone
LZ_U	Upper limit of DNLD Linear Zone
P_N	Points that define the quadratic Bézier curve
PFD	Primary Flight Display
SA	Situational Awareness
SVS	Synthetic Vision System
Vmo / Mmo	Maximum Operating Speed / Mach Number

1.2. Situational Awareness (SA)

Cockpit primary flight displays (PFD) present a multitude of information, principally related to the control and supervision of the desired aircraft trajectory. The former is a tactical task which involves relatively tight control and tracking of a desired parameter, such as aircraft altitude. The latter is a broader strategic task which entails the maintenance of proper Situational Awareness (SA) by the pilot.

Endsley [1] defines three levels of S.A.:

Level 1: Perception of the elements in the environment.

Level 2: Comprehension of the current situation.

Level 3: Projection of the future status.

The basic PFD depictions of airspeed, altitude, vertical speed, and heading directly address Level 1 SA for their respective parameters, but they provide limited Level 2 and Level 3 information as they represent a "snapshot" of the instantaneous aircraft trajectory. Hiremath et al. note that trend information is also difficult to obtain from tape displays [2]. Rate-aiding trend vectors and preselector "bugs" are often added to airspeed and altitude tape displays in an effort to provide projection (i.e. Level 3) information, but this capability is compromised with conventional displays, because the values are often "parked" off-scale due to the limited range of linear scales. This is sometimes addressed by presenting the saturated value in numerical format, but English states that this partial solution *"…is limited to one or two values and requires cognitive rather than perceptual processing"* [3].

The saturation of linear scales and their predictors exemplifies their basic shortcoming: there is an inevitable trade-off between scale range, scale resolution, and display legibility. Optimization of any pair of these elements must be at the expense of the third, or other concessions: Mejdal et al.

note that the ability to truncate electronic scales is leading designers to display solely the current value which *"can easily lead them into designing a poorer interface"* [4]. This compromise is unavoidable with mechanical instruments, where the scale parameters are fixed by the display mechanism, but this need not be the case for electronic flight displays. This paper addresses the development from first principles of a novel PFD tape display format for the electronic display era, when the mechanical scale constraints no longer apply. A brief review of analog display challenges situates the need for the new technology in a historical context.

1.3. A historical perspective

Before the advent of tape displays, round-dial mechanical instruments ruled the cockpit. As aircraft performance increased and flight envelopes expanded, this imposed increasing challenges on these "steam" gauges. The resulting compromises led to the well-known problems with 3-pointer altimeters [5] , resulting in their being prohibited for Transport aircraft applications (Figure 1).

Figure 1. "Classic" analog altimeters.

Tape displays have gradually supplanted round-dial displays in Electronic Flight Instrument Systems (EFIS) applications, and they have been widely adopted in aircraft cockpits since the 1970s. Non-linear display markings have been part of aviation since its earliest day, and some of these early designs have shown considerable creativity in addressing the human factors challenges of mechanical instruments (Figure 2).

Figure 2. "Classic" non-linear radar altitude and airspeed displays.

The earliest tape displays were aptly named, as they used physical "tapes," spooled through bobbins inside the instrument. Due to the conservative character of aviation progress, the first EFIS displays contained simple pictorial representations of their round-dial electro-mechanical forebears (Figure 3). These early electronic tape displays were generally linear, but sometimes contained non-linear elements, or combinations of both approaches as Figure 3 illustrates.

Figure 3. "Round-dial" and tape electronic engine displays.

With few exceptions, all of these displays share a common trait: the display scale, whether linear or non-linear, is static, forcing the compromise that has already been discussed. The problem is least evident for engine instruments, which have a relatively fixed and narrow operating range, although some newer systems change the scale display to accommodate the different requirements of a turbine start cycle. Airspeed scales have proven more challenging, particularly for high performance applications, because of the need for high resolution (± 1 knot, typically) over a very broad range. For this reason, tape airspeed displays usually have a narrow scale range of the order of ± 30 knots. The tape display of aircraft altitude is even more challenging, because of a typical required operating range from sea-level to 50,000+ feet and a required resolution of ± 20 feet. Typical EFIS tape altimeters have a maximum scale range of approximately ± 500 feet, so the majority of the aircraft's altitude envelope is always out of view.

2. DESIGNING FROM FIRST PRINCIPLES

Dynamic Non-Linear Display (DNLD) technology aims to address the preceding shortcomings by constructing an idealized tape display using human factors first principles. For conciseness, the experimental display is addressed as DNLD, although this terminology represents the end-point of the analytical process, and was not a going-in assumption.

DNLD explicitly addresses Endsley's three SA levels via the smooth blending of a linear fine-tracking region (for SA Level 1) with two non-linear scales anchored to meaningful upper and lower end-points (Level 2 SA) that change dynamically to ensure that critical values, predictors, and pre-set bugs never saturate (Level 3 SA).

The basic DNLD scale comprises a central linear zone, flanked by two non-linear scales that extend from the extremes of the linear zone to the edges of the tape display. The resulting tape can be oriented horizontally or vertically according to its function (e.g. altitude or heading), but the same concepts apply to both implementations.

2.1.1. Linear tracking zone

The central part of the DNLD comprises a moving linear scale with the current value (P) of the measured parameter (airspeed, altitude, heading, etc.) at the scale's mid-point. A linear scale is used in this region to facilitate closed-loop fine-tracking of the displayed parameter. This zone is also functionally identical to a traditional linear tape display, which ensures that pilots are immediately familiar with the fundamental operation of the display.

English notes that *"expanded range displays did not adversely affect the speed or accuracy of retrieval of center system value"* [3]. The final iterations of the DNLD research protypes allocated one-third of the display to the central linear region, with the remaining two-thirds equally allotted to the non-linear scales above and below the linear region, but this apportionment is subject to further investigation. The lower and upper extreme values of the linear zone are identified as LZ_L and LZ_U respectively in the material that follows.

The resolution and markings of the linear DNLD zone were established using the requirements of the tracking task. For example: an airspeed discrimination of ± one knot has historically been provided, with an altitude discrimination of ± 20 feet. The linear index markings and scale numerals adopted current conventions to optimize the learning transfer from traditional displays.

2.1.2. End-point anchors

The end-point anchors (EPA) are key elements of the DNLD, as they supplement the Level 1 SA obtained from the linear zone and add Level 2 and 3 SA. The EPAs define the extreme upper and lower extremes of the DNLD tape, and their values are selected to have a logical connection to the parameter being displayed and the associated SA implications. The EPAs may be static or floating values, depending on these considerations (Section 3.3). Table 2 illustrates sample characteristics for the lower (EPA_L) and Upper (EPA_U) values for airspeed, altitude and heading parameters.

Table 2. DNLD end-point anchor examples.

Parameter	Lower EPA[1] (EPA_L)	Upper EPA[1] (EPA_U)
Airspeed	0 KIAS or min. displayable airspeed	Vmo / Mmo[3]
Altitude	0 feet	2x current altitude

[3] Maximum operating speed/Mach number.

		At least 5,000 ft
Heading	Current heading –179˚	Current heading +179˚

[1]These values can float if necessary. For example, the upper airspeed EPA can exceed Vmo/Mmo if the parameter value approaches the limit, in order to avoid saturating the scale.

The EPAs are key parameters of the DNLD scale design. They ensure that a broad range of values is always displayed graphically (e.g. the entire airspeed envelope from zero to Vmo/Mmo), while having the flexibility to expand if the preset limits are approached. The broad scale coverage compared to traditional linear displays minimizes the chance of predictors and bugs (such as airspeed and altitude preselectors) going off-scale. Correct selection of the EPAs also ensures that vital information (such as a terrain depiction in the altitude display) always remains in view, thereby facilitating Level 2 and 3 SA.

2.1.3. Non-linear scales

The upper and lower non-linear scales connect the linear zone with their respective EPAs to cover the full range for the parameter being displayed. These non-linear scales are defined by a number of parameters:

1) The end-points of the upper non-linear scale are defined by LZ_U and EPA_U.

2) The end-points of the lower non-linear scale are defined by LZ_L and EPA_L.

3) Both non-linear scales constantly and dynamically adjust to fit these end points, contracting away from the current parameter value *P* in the center of the linear display.

4) The non-linear scale algorithms (stemming from (3) above) are continuously adjusted to avoid any discontinuities in values *or scale gradients* at the intersection of the linear and non-linear regions. This is to preclude any distracting display “jumps” across this transition when the displayed values are changing, as discussed below.

From these characteristics, it can be seen that the upper and lower scales are not necessarily symmetrical, because the two EPA’s that define their endpoints may not be equally spaced from the current parameter value. For example, at high aircraft speeds, the airspeed parameter will be closer to the Vmo/Mmo EPA than the minimum displayable airspeed EPA. Conversely, the non-liner scales would be symmetrical for a typical DNLD heading display, where both EPAs are ±179˚ from the current heading value.

The mathematical definition of the non-linear scale can take many forms, such as polynomial, logarithmic, exponential or trigonometric. The current implementation in the DNLD protypes uses quadratic or higher order Bézier curves to satisfy the preceding scale requirements. Bézier curves have several advantages for this application: unlike log scales, they can display zero values; they are smooth and can be scaled indefinitely; furthermore, their start and end points are tangent to the first and last section of the defining Bézier polygon, thereby avoiding slope discontinuities at the curve end-points, per requirement (4) above. For these reasons, Béziers are used extensively to smooth animation trajectories in user interface design – a close parallel to the scale animation characteristics required for DNLD.

The parametric equation for a display parameter $B_L(t)$ on the lower non-linear region of a quadratic Bézier curve is:

$$B_L(t) = P_L + (1 - t^2)(LZ_L - P_L) + t^2(EPA_L - P_L) \; where \; 0 \leq t \leq 1 \tag{1}$$

Where:

$B_L(t)$ is the Bézier display value, in parametric form

EPA_L is the lower End Point Anchor

LZ_L is the lower extreme value of the linear zone

P_L is the parameter that defines the quadratic Bézier curve

t is the control parameter that sweeps the Bézier curve from LZ_L to EPA_L

Similarly, the display parameter $B_U(t)$ on the upper non-linear region of a quadratic Bézier curve is defined by:

$$B_U(t) = P_U + (1 - t^2)(LZ_U - P_U) + t^2(EPA_U - P_U) \; where \; 0 \leq t \leq 1 \tag{2}$$

Where the symbols have their previous meanings, mapped to the upper limits instead of the lower limits.

The derivative of the lower Bézier curve is given by:

$$B_L{}'(t) = 2(1 - t)(P_L - LZ_L) + 2t(EPA_L - P_L) \tag{3}$$

The corresponding derivative for the upper Bézier curve is given by:

$$B_U{}'(t) = 2(1 - t)(P_U - LZ_U) + 2t(EPA_U - P_U) \tag{4}$$

By definition, $(t) = 0$ at the intersections of the linear and non-linear zones, so the derivatives at these points reduce to:

$$B_L{}'(t) = 2(P_L - LZ_L) \tag{5}$$

and

$$B_U{}'(t) = 2(P_U - LZ_U) \tag{6}$$

Because the linear zone only has a single scale, the non-linear scale gradients at these points must equal each other $(B_L{}'(t) = B_U{}'(t))$ and they both must equal the gradient of the linear zone (per 2.1.3 above).

Accordingly:

$$(P_L - LZ_L) = (P_U - LZ_U) \tag{7}$$

Rearranging:

$$(LZ_U - LZ_L) = (P_U - P_L) \tag{8}$$

Equation (8) defines a simple relationship between the constantly varying Bezier parameters (P_U, P_L) and the fixed linear scale range $(LZ_U - LZ_L)$. Application of this constraint into equations (1) and (2) above achieves the desired matching gradients between the linear and non-linear zones.

2.2. Consolidated DNLD

The consolidated DNLD is a composite of the linear zone and the upper and lower non-linear scales, terminating at the EPA_U and EPA_L respectively. The DNLD is supplemented by the traditional graphic predictors (e.g. airspeed and altitude trend lines) and preset "bugs" (e.g. airspeed and altitude preselect values). Figure 4 shows a decomposition of the main DNLD display elements for the depiction of airspeed and altitude information.

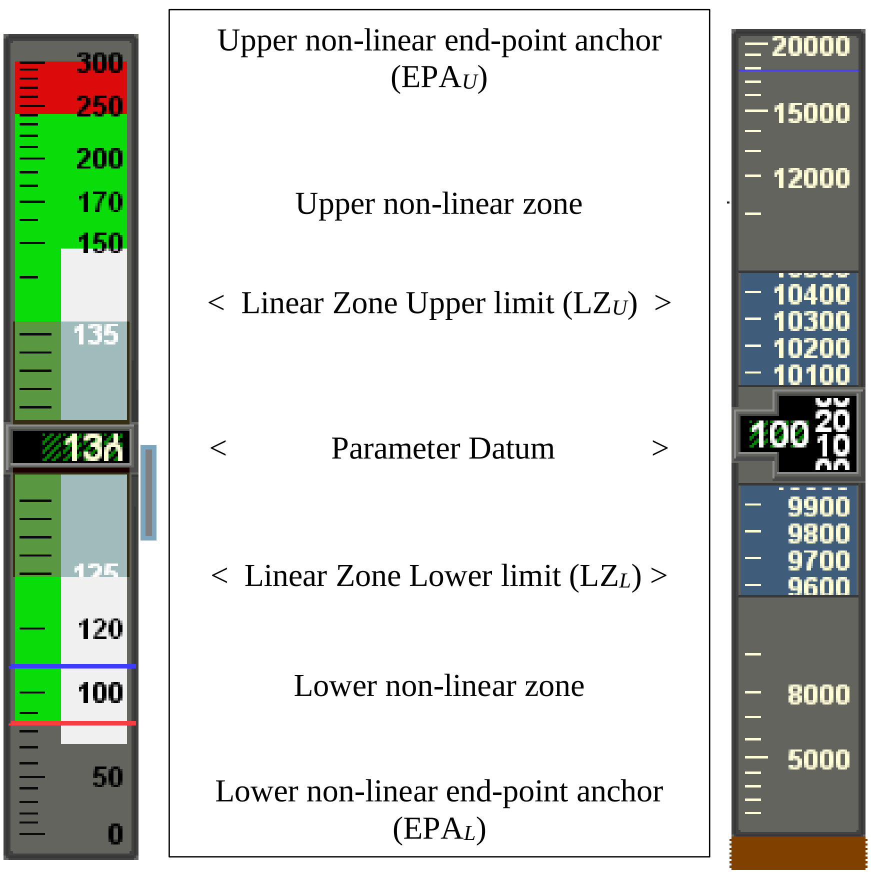

Figure 4. DNLD Essential Elements.

Figure 5 shows DNLD implementations of airspeed, altitude, and heading integrated into a simple PFD and a Synthetic Vision System (SVS) display, as trialed in the P180 Avanti aircraft used to develop the technology.

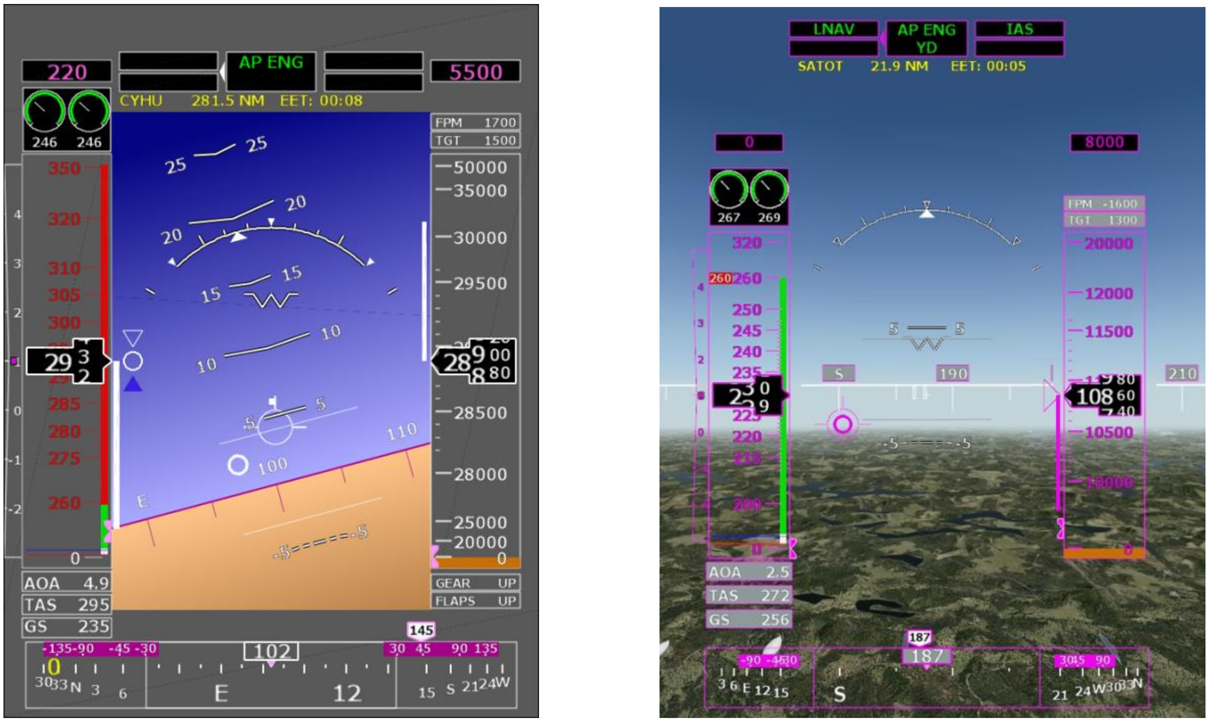

Figure 5. DNLD PFD and SVS displays.

3. DNLD DEVELOPMENT PROCESS

DNLD development has followed a progression from TRL 1 through TRL 7, starting with desktop simulations, followed by human factors simulator evaluations, and culminating in developmental flight testing in Cert Center Canada's (3C) P180 Avanti research aircraft (Figure 6). Beta DNLD software was also integrated for an evaluation using the Harvard aircraft operated by the Flight Research Laboratory of Canada's National Research Council (NRC-FRL). The objectives of the development process were:

1) To validate the basic concept of DNLD, initially for the PFD depiction of airspeed, altitude, and heading information.

2) To determine the optimum display allotment between the linear and non-linear DNLD zones.

3) To establish heuristics for the DNLD end-point anchors for each displayed parameter.

4) To characterize DNLD behavior during high rates-of-change of the displayed parameters.

5) To assess the impact of DNLD on pilot SA.
6) To address phantom scale markings (see section 3.6 below)

Figure 6. 3C DNLD Simulator and P180 Avanti development platforms.

3.1. DNLD validation.

Perhaps the strongest validation of the DNLD concept was obtained outside the dedicated DNLD experimental context. DNLD is permanently hosted as the standard PFD on 3C's human factors simulator, and it was also the default display at the research station (copilot's side) of 3C's P180 test vehicle. Throughout the operation of these two systems, only a single subject (from many hundred individual exposures) remarked on the unusual nature of the primary display format, when DNLD was not the focus of the experiment. Pilot capture and tracking performance were not adversely affected by the novel format. Conversely, while pilot performance was satisfactory during the NRC trials, subjective debriefing assessments tended to focus on the display's unique attributes, rather than the performance obtained. This indicates that future experimental DNLD assessments could introduce an element of bias if excessive emphasis is placed on briefing the test subjects on DNLD's unique display characteristics (which has proven unnecessary, in any event, for normal task execution). This confound can be addressed and quantified in future DNLD experimental evaluations by the use of a control group that is briefed extensively on the task to be performed but *not* explicitly briefed on DNLD's unique characteristics.

A striking feature of DNLD operation, which requires first-hand exposure to validate, is the smoothness and integrated nature of the display. For example, the user is generally unaware of the asymmetries between the upper and lower non-linear zones, and of the many non-linearities and constant adaptations performed to blend the three zones. These asymmetries are masked by the compression at the extremities of the scales, which minimize their visual impact, and by the scale continuity criterion already discussed. For altitude SA, pilots are also intuitively accustomed to the asymmetry between the vertical extent of the sky above the local horizon (infinite) versus the finite distance below the horizon to ground level. Ironically, the DNLD altimeter tape is more conformal than a traditional altimeter tape in this respect, because the DNLD scale contracts away from the local level, exactly as the real-world optical field behaves. The first few degrees of angular DNLD deviation from the local horizon represent a relatively small vertical offset, which increases trigonometrically as the visual angle increases towards the vertical, where the displacement tends towards the infinite as the vertical offset angle approaches 90 degrees. In practical terms, this means that the DNLD rendering of altitude on a Head Up Display (HUD) would be more nearly conformal to the external visual field than a linear altitude display.

3.2. Linear/Nom-linear display allocation.

Developmental versions of DNLD incorporated means to rapidly adjust the ratio of the linear and non-linear zones, in real-time. The initial setting of this parameter simply divided the tape into equal thirds, and no cogent reason was found to change this default setting, even after evaluating several other proportions. A convenient side-benefit of the real-time adjustable linearity parameter was the ability to instantly convert DNLD into a conventional linear display for experimental control-group purposes by setting the linear zone to 100 percent coverage.

3.3. End-point anchors heuristics.

The EPA settings proved pivotal to deriving the greatest DNLD SA benefits, although they were not critical to the usability of the DNLD because the linear fine-tracking zone is unaffected by the EPAs. In general, three different desired EPA characteristics have been identified:

- Fixed
- Adaptive
- Floating

3.3.1. Fixed EPAs

Fixed EPAs are static. The display of compass information is best suited to fixed EPAs at ± 179˚ from the current aircraft heading (Table 2). This is because the heading can never take values outside 0˚ to 359˚, so there would be no benefit to moving the EPAs beyond this range. The fixed EPAs in the DNLD rendering of heading information are clearly evident in Figure 5.

3.3.2. Adaptive EPAs

Adaptive EPAs are generally static, but adapt as they are approached. The display of airspeed information is best accommodated by adaptive EPAs: the default values include the lowest displayable airspeed up to Vmo/Mmo (Table 2), with the upper values increasing as the airspeed approaches Vmo/Mmo. This facilitates Level 2 and 3 SA by allowing the airspeed trend vector to remain "on scale" during the high speed regime. At all other times, the airspeed scale encompasses the entire aircraft flight envelope. Figure 5 shows the airspeed behavior above Vmo/Mmo (left illustration), contrasted with nominal behavior inside the flight envelope (right illustration).

3.3.3. Floating EPAs

Floating EPAs adjust constantly depending on the parameter value. Aircraft altitude is best displayed using a floating EPA implementation, because of the very broad limits of the displayed altitude range. As indicated in Table 2, the lower EPA is generally set at zero altitude (mean sea level) although this value can expand slightly to display altitudes below sea level, if required. Using sea level as the EPA_L ensures that the cross-section of the terrain elevation is always visible on the altitude display, even when the terrain is well below the aircraft, in contrast to linear displays which typically only have a range of a few hundred feet. The constant display of terrain cross-section information adds an element of Level 2 and Level 3 SA as the terrain relationship to the aircraft trajectory is always visible. For example, a 1-minute altitude predictor intersecting the terrain depiction would clearly indicate an impending terrain conflict. This only works with linear displays for very low vertical rates, because the 1-minute predictor is off-scale in relation to the altitude readout for high vertical rates.

Several options were available during development tests for establishing EPA_U, including accommodating the aircraft's ceiling at all times. This was discarded in favor of a simple heuristic to establish the EPA_U at twice the aircraft's current altitude with a hard minimum of 5,000 feet. This expands as the aircraft climbs until the peak EPA_U corresponds to the aircraft's ceiling. A small scale extension is added as the aircraft approaches its ceiling, to ensure that the altitude display never saturates.

The resulting altitude display has the benefit of becoming increasingly sensitive (i.e. a larger scale) near the current altitude, and at lower altitudes, while constantly showing the terrain elevation regardless of the aircraft's altitude. As already indicated, the non-linear altitude display is also more conformal with the outside world than a linear altitude tape. Finally, this implementation guarantees that altitude preselectors and trend lines don't typically saturate off the end of the display scale, which is always at least 5,000 feet above the current altitude. In contrast, a typical linear altimeter scale has a range of only ± 500 feet, so display and predictor saturation is the norm.

3.4. High rate-of-change assessment.

A key subjective evaluation of DNLD was an assessment of its performance during high rate-of-change maneuvers. This was initially evaluated using a dedicated desktop application that allowed real-time adjustments of airspeed and altitude rate-of-change for a DNLD and conventional display in parallel. DNLD was then evaluated in the 3C human factors simulator during single- and multi-axis high-rate maneuvers, such as Cuban eights and low and high-speed unusual attitudes. High-rate tests were also performed in NRC-FRL's aerobatic Harvard aircraft. No high-rate testing was performed in the P180 aircraft because it is not certified for acrobatic maneuvers.

The results of these tests were very positive. The simulations have shown that the application of the EPA_U heuristics (section 3.3) has resulted in unified DNLD graphic displays that are usable from orbital airspeeds and altitudes all the way to a standstill at zero altitude, at rates of change in excess of 60,000 ft/minute. As expected, the linear regions move rapidly during such extreme maneuvers, but this has no impact on pilot performance, because these maneuvers do not entail fine-tracking tasks, and the effect is no worse than for a conventional linear display. Conversely, the non-linear zones move smoothly and predictably. This is to be expected given the use of Bézier curves to manage rapid optical flow in computer interfaces.

Display parameters (such as altitude tics and captions) accelerate smoothly and predictably (from an optical flow perspective) from the edges towards the center of the display, in concordance with the dynamic scale changes performed by DNLD. It is easy to graphically gauge this optical flow to determine how rapidly a limit (such as an airspeed limit or an altitude floor) is being approached. These characteristics should make the use of DNLD practical for military HUD implementations, which largely shun tape displays because of their adverse characteristics during aggressive maneuvering. In particular, the languid motion of the DNLD displays obviates the false roll cues caused by traditional airspeed and altitude tapes moving in opposition to each other during rapid climbs or descents.

3.5. Pilot SA assessment.

Although only limited quantitative pilot SA experimental assessments have been conducted, there is undoubted face validity that several of the characteristics already described contribute to improved pilot SA at all three levels. These include legibility under extreme dynamic conditions; constant depiction of the entire flight envelope and the terrain plane; automatic higher resolution around the current displayed value; more conformal altitude display with increasing resolution at lower altitudes; and non-saturation of trend vectors and preselector indexes.

An obvious application for the enhanced SA provided by DNLD is for Electronic Standby Instrumentation Systems (ESIS), which typically incorporate linear tape displays of airspeed, altitude and heading. In the worst case, these stand-alone instruments must provide the entire air-picture for the crew in a very small display, so any improvement in SA or workload reductions would be very beneficial in this application.

3.6. Phantom scale markings.

An emergent DNLD characteristic that was identified and addressed during the development process was the handling of the appearance and disappearance of tick-marks and captions in the non-linear zones. The non-linear scales must obviously introduce and subtract markings to properly populate the scale-space across the full range of the possible displayed values, particularly for the altitude scale. This apparently unique DNLD characteristic is not conceptually different from linear tape displays, where numbers and markings appear and disappear at the scale extremes as the parameters change, but the phenomenon uniquely occurs in the middle of the DNLD non-linear scales. A straightforward mitigation appears to have satisfactorily addressed this issue: the use of fade-in and fade-out for these “phantom” markings over a period of 2-3 seconds. This simple adjustment eliminated distractions caused by the sudden appearance and disappearance of the phantom markings. A related issue concerned the selection of *which* intermediate markings to display, which was addressed using a number of heuristics:

1) The parameter values should be distributed relatively uniformly across the non-linear zones to avoid voids and clutter, thereby aiding legibility and usability.

2) Critical values must be displayed at all times (e.g. thousand-foot markers near the current altitude, 5,000 foot markers, etc.)

3) Phantom markings cannot display arbitrary or meaningless values. For example, DNLD might calculate an ideal intermediate non-linear altitude of 13,963 feet to display, but the pilot would clearly not be interested in such a marking.

These constraints have been fully addressed in the current DNLD prototypes, but the specific algorithms are beyond the scope of this article.

4. CONCLUSIONS

The Dynamic Non-Linear Display represents an effort to develop a tape display from first principles that reconciles the conflicting demands of high resolution, a broad scale range, and good legibility, particularly under dynamic conditions. DNLD has been evaluated through TRL-7 via desktop, simulator and flight evaluations, and the concept has so far fulfilled these objectives.

A number of key DNLD concepts have been identified and refined, including the division of the tape into equally-sized linear and dual non-linear zones. Bezier curves were found ideal for the implementation of the DNLD algorithms for their excellent optical flow and smoothness. Several heuristics were identified to establish the end-point anchors defining the Bézier curves. The resulting display proved legible through all flight regimes and did not allow trend vectors and preselector datums to saturate. Fine-tracking performance in the linear zone was generally equivalent to conventional displays, but DNLD demonstrated a potential to enhance Level 2 and Level 3 pilot SA due to the significantly expanded usable display range, which always keeps critical parameters (such as the terrain surface for the altimeter tape) in view.

DNLD would benefit from ongoing research to advance the concept through TRL-8 to TRL-9. The basic technology is ready for further refinement and formal experimental evaluation using established SA and workload assessment tools such as the Situational Awareness Rating Technique (SART); Situation Awareness Global Assessment Technique (SAGAT); the Bedford Workload Rating Scale; or NASA’s Task Load Index (TLX). One caveat for future experimenters is to use a control group whose test subjects are not extensively briefed on DNLD prior to their assessments. This is to avoid confounding the subjects’ assessments of DNLD’s performance outcomes with its unique characteristics. Potential near-term applications for DNLD include the airspeed altitude and heading tapes in PFDs, standby displays, HUD and SVS displays.

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BIOGRAPHY

Dr. John Maris has been an experimental test pilot for over 35 years. He is an Aviation Week and Space Technology Laureate, and was awarded Canada’s senior aeronautical prize, the Trans-Canada (McKee) trophy, for his contributions to Canadian aerospace. Dr. Maris is a Member of SFTE, a Fellow of the Canadian Aeronautics and Space Institute, a Fellow of the Royal Aeronautical Society, and an Associate Fellow of AIAA and of the Society of Experimental Test Pilots.

Dr. Maris is a practicing aeronautical engineer with a Ph.D. in Aviation Safety and Human Factors. John is currently the Chief Test Pilot for Pratt and Whitney’s Hybrid Electric Propulsion (HEP) Technology Demonstrator aircraft. He was inducted into the Canadian Aviation Hall of Fame in June 2018.

Finlay Wynd Smith is in the Bachelor of Aerospace Engineering program at Carleton University (Ottawa), with a concentration in Aerodynamics, Propulsion and Vehicle Performance. Finlay has been on internship with Cert Center Canada, where he has participated in a number of aerospace R&D projects, including Pratt & Whitney’s Hybrid Electric Propulsion (HEP) flight test program. Finlay is a graduate of the International Baccalaureate Diploma program from the International School of Geneva, and is a student member of SFTE.

APPENDIX A DNLD Patents

Patent Name	Country	Patent #
Electronic Non-Linear Aircraft Dynamic Parameter Display	Brazil	PI0314374-0
Electronic Non-Linear Aircraft Dynamic Parameter Display	Canada	2494050
Electronic Non-Linear Aircraft Dynamic Parameter Display	China	ZL 03823675.3
Electronic Non-Linear Aircraft Dynamic Parameter Display	France	1546655
Electronic Non-Linear Aircraft Dynamic Parameter Display	Germany	1546655
Electronic Non-Linear Aircraft Dynamic Parameter Display	Italy	1546655
Electronic Non-Linear Aircraft Dynamic Parameter Display	Japan	4246155
Electronic Non-Linear Aircraft Dynamic Parameter Display	U.K.	1546655
Electronic Non-Linear Aircraft Altitude and Vertical Speed Display	U.S.A.	7062364 B2
Electronic Non-Linear Aircraft Dynamic Parameter Display	U.S.A. CIP	7725221 B2