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Towards Optimized Profile Descents at Malta International Airport through Revised Approach Procedures

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Nomenclature

ADS-B	= Automatic dependent surveillance-broadcast
AIP	= Aeronautical information publication
AMSL	= Above mean sea level
ARP	= Aerodrome reference point
ATC	= Air traffic control
ATCO	= Air traffic control officer
BADA	= Base of aircraft data
CI	= Cost index
CO_2	= Carbon dioxide
FAF	= Final approach fix
FMC	= Flight management computer
FTE	= Flight technical error
GNSS	= Global navigation satellite system
GRIB	= General regularly-distributed information in binary form
IAF	= Initial approach fix
IF	= Intermediate fix
ICAO	= International civil aviation organization
IFR	= Instrument flight rules
ILS	= Instrument landing system
LMML	= ICAO CODE for Malta International Airport
MCDU	= Multifunctional control display unit
MIA	= Malta International Airport
NCEP	= National centers for environmental prediction
NOTAM	= Notice to airmen
OPD	= Optimal profile descent
PBN	= Performance based navigation
PDF	= Probability density function
RF	= Fixed radius
RNAV	= Area navigation

RNP	= Required navigation performance
RNP-AR	= Required navigation performance authorization required
SID	= Standard instrument departure
STAR	= Standard instrument arrival route
TF	= Track to fix
TOD	= Top of descent
VFR	= Visual flight rules

Abstract

Traditionally, aircraft descend from cruise level towards the aerodrome in a stepped manner as directed by Air Traffic Control to ensure safe separation between aircraft, particularly in the terminal area. A descent methodology that is now being preferred is that of optimised profile descents (OPD). In OPDs, the aircraft descends from the top-of-descent (TOD) point towards the aerodrome following a smooth, continuous descent profile that is optimal from an operational perspective of choice, until it intersects the final approach glide path such as that of the Instrument Landing System (ILS). OPDs are advantageous because they consume less fuel and generate fewer emissions than their stepped counterparts.

This paper presents a proposal of new approach procedures for use in the approaches to Malta International Airport (MIA) that will facilitate the introduction of OPDs. With around 28,000 aircraft movements per annum at MIA, this can be achieved by giving Air Traffic Control Officers (ATCOs) a selection of approach procedures on which to direct in-trail inbound and outbound aircraft without imposing altitude constraints. The discussion includes a study of current procedures, a statistical analysis of historical radar plots, the presentation of the proposed approaches, and a forecast of the potential gains in terms of fuel burn and emissions expected through fast-time simulation.

1 Introduction

Malta International Airport (MIA) is a small to medium sized airport having a peculiar characteristic in that the overwhelming majority of flights operate via north-westerly routes overflying western Sicily. The work associated with this paper has been carried out within the CLEAN-FLIGHT project, a research project funded by the Maltese National Research & Innovation Programme involving the University of Malta and QuAero Ltd., an aerospace consultancy company focusing on aircraft operations. The project aims to lead the way to the introduction of optimal approaches to and departures from MIA for the reduction of greenhouse gases in the Maltese airspace.

The work presented in this paper follows on earlier work in which the methodologies associated with the design of standard instrument departures (SIDs) and standard arrival routes (STARs) for the Maltese airspace have been presented [1]. In this paper, new approach procedures for runways 13 and 31, which are the two most heavily used runways, are presented. These runways are equipped with Instrument Landing Systems (ILS) certified to CAT I, but flight checked to CAT II standards [2]. An in-depth study that has been conducted to quantify the economic and environmental gains expected with the adoption of the proposed procedures is also discussed.

2 Performance Based Navigation

There is a global initiative to improve the efficiency of aircraft operations whilst still ensuring safety, regularity, expedition and sustainability. The implementation of the performance-based navigation (PBN) concept has been recognized as a key enabler to improved flight efficiency, as identified by major programmes such as NextGen in the US and SESAR in Europe [3].

PBN incorporates the area navigation

(RNAV) and the required navigation performance (RNP) concepts. RNAV is defined as a method of instrument flight rules (IFR) navigation that permits aircraft operation on any desired flight path within a particular navaid coverage zone. RNAV has been further improved through the introduction of RNP procedures, which use the Global Navigation Satellite System (GNSS) and on-board technology to monitor in real time the aircraft position and the achieved navigation performance. PBN allows aircraft to fly three dimensional routes in the most flexible and accurate way currently considered possible. ICAO Doc 9613 states that: “The PBN concept represents a shift from sensor-based to performance-based navigation” [4]. PBN routes are defined by the minimum required navigation performance in terms of accuracy, integrity, availability, continuity and functionality required for operation within a given airspace.

One of the key-enablers of the PBN concept is the capability that allows the aircraft to fly a predefined ground track with consistency, predictability and reliability and in different weather conditions. The fixed radius (RF) leg manoeuvre is an integral part of flying such a predefined ground track, as it allows aircraft to follow a circular track defined by a constant radius traversing from an initial fly-by waypoint to another fly-by waypoint [5].

In PBN, turns can also be performed through the connection of three waypoints using track to fix (TF) segments. For fly-by waypoints, the flight management computer (FMC) calculates the turn anticipation distance required to connect to the following leg based on the current ground speed, the programmed bank angle and the change in track required. From observation studies conducted by the MITRE Corporation of the United States, it has been shown that due to different implementation of standards adopted the by FMC, aircraft compute the anticipation distance for TF-TF legs differently. This results in variations in the flight paths followed when executing such a turn [6]. This lack of accuracy and predictability compromises the concept defined by PBN and is an issue when predicting the optimal flight path, particularly in 4D navigation.

In another study for turns using the RF leg, also carried out by MITRE Corporation [7], it was concluded that an aircraft established on the tangential path leading to a RF turn will have a flight technical error (FTE) that falls within the limits provided by the relevant RNP. The FTE represents the extent of the ability of the aircraft guidance system to follow the flight path defined within the navigational database. Lateral conformance was also proven when RF turns were performed in the presence of a tail wind. The authors of [6] suggest that turns in the terminal area should be defined using the RF legs when possible, due to the accuracy and predictability associated with such procedures being greater than that of turns performed using TF-TF segments. The accuracy provided by the RF turn makes it suitable for use in the design of PBN routes.

Currently, use of RF legs is limited to aircraft with FMCs that are approved for Required Navigation Performance Authorization Required Approach (RNP-AR APCH) navigation. However, ICAO is working towards establishing an RNP Advanced Navigation System incorporating the RF leg without the need of an authorization approval [3]. RNP-AR APCH is a navigation method that allows a higher level of navigation performance with the improved capacity to solve accessibility problems to airports located in environments with complex obstacles. This is possible due to the precision, integrity and functional capacities of the equippage of RNP-AR APCH approved aircraft. The high precision provided by this type of approach is ensured by redundant systems through dual GNSS sensors, dual FMS systems, dual air data systems, dual autopilots and a single inertial reference unit [8].

3 Problem Definition

The Boeing 737 and Airbus A320 aircraft families constitute the large majority of the traffic flying in and out of MIA (ICAO code LMML). Although the flight management systems (FMSs) installed on such aircraft are capable of computing an appropriate TOD point for a particular cost index (CI) and upper wind forecasts, the computation, being aircraft centered, does not include considerations such as ATC constraints and aircraft separation. When air traffic controllers instruct changes in headings, altitude, and speed in order to maintain adequate separation from other aircraft, the actual route flown, deviating from that planned by the FMS, becomes inefficient in terms of fuel and carbon emissions [9].

The effect of this limitation is further aggravated by the fact that LMML lacks published arrival routes, making it more difficult to plan and implement optimal descents. The lack of arrival routes causes dispersion in the flight paths followed by aircraft flying towards the final approach fix, with the result that sub-optimal trajectories are being followed both laterally and vertically. The trajectories followed may include lateral extensions and stepped descents due to the lack of planning strategies, which, in turn, result in an increase in the fuel burn and emissions.

The initial approach into Malta International Airport can be performed under either VFR or IFR, with the final approach on the main runways often being performed with the aid of the ILS. Recently, Malta's AIP was updated with a number of RNAV waypoints forming a T-bar structure for the main runways as seen in Fig. 1 [2]. These waypoints give both pilots and air traffic controllers additional flexibility to support the better planning of a descent. They are used by ATC to issue direct clearances to arriving traffic to one of the fly-by waypoints before intersecting the final approach fix. However, the inherent limitation of fly-by waypoints still causes dispersion in the tracks flown when approaching the ILS glide slope. The variation in the flight paths followed during the approach is mainly noticed from the recordings of aircraft performing the base turn.

The design of accurate and predictable flight paths is required as the first step towards optimized profile descents into LMML. In this paper, the revised approach routes at a strategic level are presented for runway 13 and runway 31. A new STAR, named EKOLA 1A is proposed for arrivals from the entry point EKOLA, which is situated to the the north-west of Malta (Fig. 2).

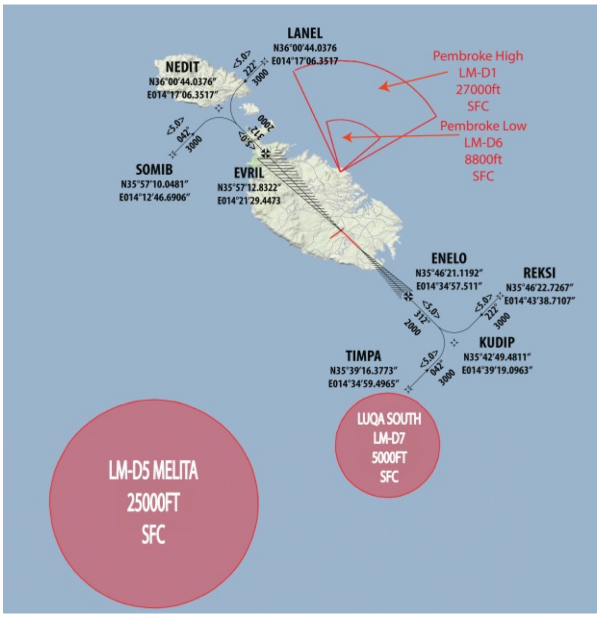

Fig. 1 The current T-bar approaches to runways 13 and 31 at LMML [2].

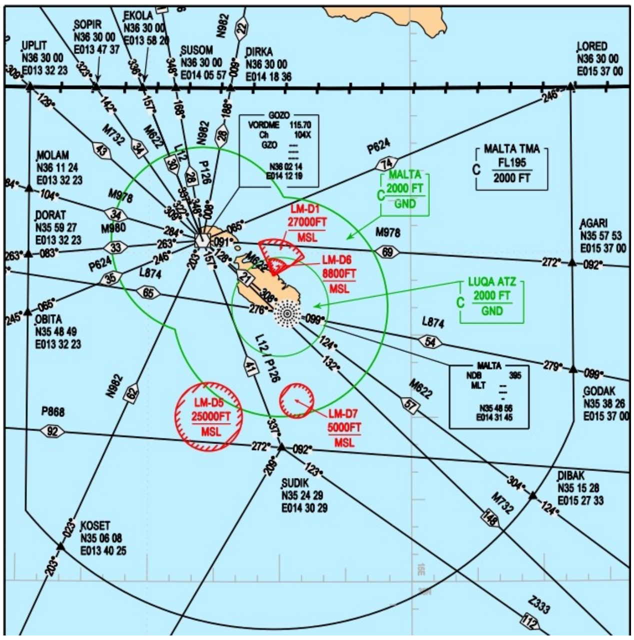

Fig. 2 Malta's Terminal Area [2].

This STAR is connected to one of the new proposed approaches to runway 31 and, through statistical analysis of actual recorded arrival trajectories, the maximum gains that could be achieved by following the proposed new route path are identified and presented as the potential gains in terms of reduction of track miles flown, reduced fuel burn and emissions.

4 Design Methodology

ICAO document 9905 (Required Navigation Performance Authorization Required (RNP AR) Procedure Design Manual) [10] was used as the guideline document to design the new instrument approaches to LMML and to connect entry points to the final approach fix, thus utilizing the expected aircraft RNP capabilities to the greatest extent.

In line with the methodology of [1], the entry points around LMML were connected directly to an initial approach fix. For changes in track of up to 90 degrees between one segment to the next, the turn was designed through TF-TF segments. In the case of turns requiring a track change greater than 90 degrees (typically base turns), these were designed using the RF leg.

Section 3.2 of ICAO Doc 9905 identifies two methods for finding the tailwind component when calculating the turn radius, namely either by using a standard tail wind component as given in Table 3-2(a) in that document, or by using statistical winds [10]. In this work, the tail wind at various altitude intervals was analysed in a statistical manner, thus avoiding the need to use over-conservative values. This approach ensures the design of the tightest RF turn for the expected range of meteorological conditions.

The Malta International Airport Meteorological Office does not currently perform radiosonde launches and only provides surface weather data from various locations around the Maltese islands. The upper winds are currently being obtained through a service provider and this data is then passed on to ATC. The meteorological data used for the analysis of the tailwind component was obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System, which provides a six hour forecast, four times per day. Forecasts from 1st January 2005 to 31st December 2012, providing an 8 year history, were downloaded for this analysis. The forecast is provided in General Regularly-distributed Information in Binary 2 (GRIB2) format, which was decoded using *wgrib2*[1] and the *degrib*[2] software. The GRIB2 file stores forecast weather data in a grid format with a defined resolution for a number of isobaric levels. The files obtained to analyse the wind over Malta have a spatial resolution of 0.5° by 0.5° at altitudes corresponding to isobaric pressure levels ranging from 1,000mb to 1mb as well as at mean sea-level. The horizontal and vertical components of wind were also obtained at the aerodrome reference point (ARP) through a bi-linear interpolation of the forecast values at the edges of the sub-grid in which the ARP lies. The altitude above mean sea level (AMSL) for each isobaric level was calculated using the recorded mean sea level pressure and the temperature forecast at the interpolated isobaric level. For altitudes below the tropopause (i.e. below 11,000m), the geo-potential height above mean sea level h in meters was found using Eq. (1), where P_0 is the recorded mean sea pressure in hPa, P is isobaric pressure level in hPa and T is the forecast temperature in $°C$.

$$h = \frac{\left(\left(\frac{P_0}{P}\right)^{\frac{1}{5.257}} - 1\right) \cdot (T + 273.15)}{0.0065} \qquad (1)$$

ICAO Doc 9905 includes the minimum and maximum speeds for different aircraft categories allowed for when following a RF turn. An analysis on the collected wind data was performed to find the maximum forecast tail wind component expected for each possible track and for an altitude interval between the start and the end of the turn. A 3° glide slope from the aerodrome's threshold was assumed to determine the altitudes along the descent trajectory. The maximum tail wind found was then used to calculate the maximum bank angle

[1] Available at : http://www.cpc.ncep.noaa.gov/products/wesley/wgrib2/

[2] Available at: http://www.nws.noaa.gov/mdl/degrib/

that would be required to correctly follow the RF leg with a 2.5 NM radius as adopted in the current T-bar structure. This resulted in a bank angle of 20.7 degrees. Section 3.2.8 of ICAO Doc 9905, however, stipulates a maximum bank angle of 20 degrees for altitudes above 492ft AGL. In order to meet this constraint, a new turn radius needed to be identified. This was done by increasing the turn radius in steps of 0.1 NM, each time finding the altitude at the start of the turn and the associated altitude interval in the turn, the maximum expected tailwind component in this interval and the resulting maximum bank angle required by a CAT D aircraft[3] to perform the turn. This process was repeated until the maximum resulting bank angle with the minimum allowed indicated airspeed was less than 20 degrees.

The analysis of the tailwind was based on the wind speed and direction and the altitudes of the forecasts recorded within the analysed period. The winds were sorted by altitude in order to create a sub-list of wind forecasts within the altitude interval being analysed. The wind records within an altitude interval were then sorted out in ascending order in terms of wind strength. A 95% confidence interval was used to discard wind records with low and high wind speeds. For each possible track the maximum recorded speed for the said confidence interval was found and these were plotted on a wind rose at 1 degree intervals (Fig. 3). For each of the maximum wind speeds measured, the tail wind component for each possible track was calculated as suggested in [11]. The resulting maximum tail wind component for each possible track was calculated and this was also plotted on a wind rose (Fig. 4).

The tail wind component was found using Eq.(2) as suggested in [11], where V_{TW} is the tail wind component in *kts*, Θ_W is the wind direction in degrees and Θ_T represents the track followed by the aircraft in degrees.

[3] Category D aircraft have a runway threshold speed (V_{at}) of between 141 kts and 166 kts.

$$V_{TW} = V \cdot \cos(\Theta_W - \Theta_T - 180) \qquad (2)$$

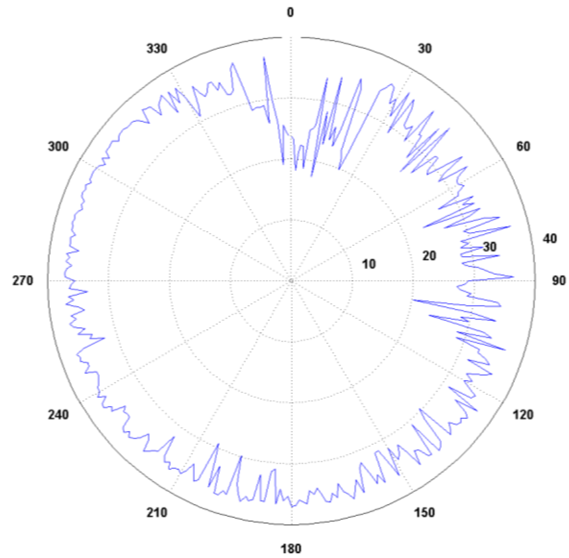

Fig. 3 Polar plot of the maximum wind speed (95% limit) over Malta at 1900-4800 ft AMSL between 1st January 2005 and 31st December 2012.

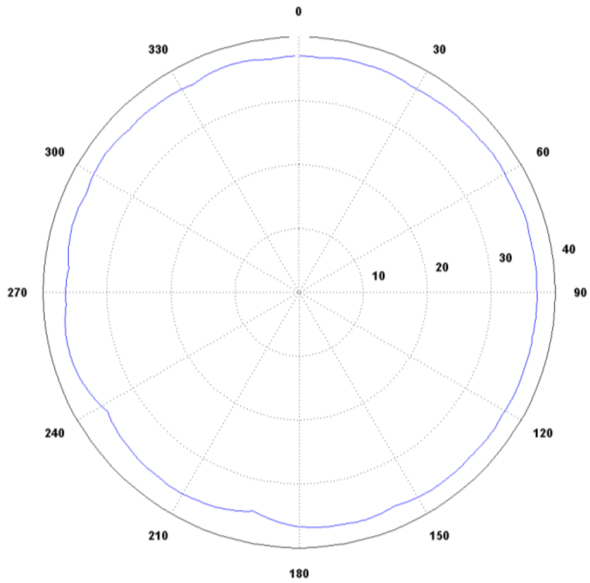

Fig. 4 Polar plot of the maximum tail wind component for each track at an altitude interval of 1900-4800 ft AMSL between 1st January 2005 and 31st December 2012.

For approaches requiring a 180 degree base turn to align the aircraft with the runway extended centreline, it was decided to start the turn abeam the final approach fixes EVRIL and ENELO shown in Fig. 1. To reduce the track miles flown to a minimum, the tightest possible turn radius had to be designed. To this effect, the process described above was used. The first attempt was to try to overlay the designed tracks on the existing T-bar structure shown in Fig. 1. The altitude intervals considered were 1,900 ft to 4,500 ft for runway 31 and 2,900 ft to 5,400 ft for runway 13. These altitude intervals were determined by applying a 3 degree glide slope from the runway threshold to the start and end of the RF turn respectively. The difference in the two intervals is due to position of the 13 and 31 FAFs with respect to the runway thresholds. For both intervals, the resulting maximum tail wind component was found to be 37 kts. ICAO Doc 9905 recommends that a CAT D aircraft performing a RF turn within the initial approach stage should have a minimum indicated airspeed of 210 kts. Converting this to true airspeed at 4,800 ft and adding a tail wind component of 37 kts, the maximum bank angle required to perform an RF turn with a radius of 2.5 NM was found to be 20.7 degrees. As explained, this bank angle just exceeds the maximum bank angle of 20 degrees suggested for RNP-AR equipped aircraft by ICAO Doc 9905. Using the incremental procedure described, a radius of 2.8 NM was found to satisfy the 20 degree bank angle limitation and therefore more suitable to connect the downwind leg to the final approach fix before intersecting the ILS glide slope.

A speed restriction of 210 kts was also introduced within the turn to ensure the aircraft does not exceed the 20 degree bank angle suggested by ICAO Doc 9905. This restriction is applied at the initial waypoint of each RF turn. It is relevant to note, however, that the maximum design bank angle allowed by ICAO Doc 9905 is conservative. Indeed, the Airbus A320 is capable of banking at an angle of 30 degrees while performing a RF leg [11]. The conservative bank angle adopted by ICAO Doc 9905 introduces an additional safety margin which, however, if not applied could result in a tighter RF turns to be flown at higher speeds. A tighter radius would reduce the total track distance flown and therefore could be considered advantageous at the cost of reducing safety margins, whilst a higher speed constraint would allow the aircraft to be flown in a clean configuration for longer before extending flaps to slow down [11]. Nevertheless, the conservative bank angle recommended by ICAO Doc 9905 was adopted in this work.

Once the turn radii were defined, the turns were connected to the relevant FAFs of the two runways. In order to obtain standardised approach patterns, IAFs were placed at least 2.5 NM upwind (parallel to the runway) from the respective turns. This distance was calculated to be that required to ensure an adequate minimum stabilisation distance between the RF turn and the IAF fly-by waypoint, following guidance material published by Eurocontrol [12]. The IAFs could then be connected to the different entry waypoints, which, in the case of this work, was EKOLA.

Holding patterns were added at the initial approach fixes (IAFs) to allow holding when required. This effectively also influenced the positioning of the IAFs, because holding patterns have 3-dimensional buffer zones around them that must not be traversed by other operational routes or holding points, etc. Given the extent of the lateral separations required, vertical separations, which, under current procedure allow for a minimum of 1,000 ft [13], were preferred. IAFs and associated holding points were consequently designed to ensure departing aircraft could procedurally be kept at least 1,000ft below the holding patterns. These holding patterns, of course, could compromise optimal flight profiles for both arriving and departing traffic but these have been introduced only with a view to provide an additional operational buffer to ensure separation should this be tactically required, with aircraft not normally requiring to hold. Indeed, the traffic density at LMML is low enough to rarely require arriving aircraft to enter a hold. In addition, it is envisaged that emerging ATM technologies based on 4-D PBN navigation will further reduce the need for their use. In this context, therefore, it has been considered acceptable for a hold pattern to also impact an outbound traffic by introducing an altitude constraint to keep it below the holding pattern when the pattern is occupied by an inbound aircraft.

The minimum altitude of the holding points was set to 6,800 ft to ensure safe separation from the earth's surface (the holding points are all above the sea). The holding patterns were designed in line with the recommendation in Section 4-10 of ICAO Doc 9905, which suggests the inbound leg to be tangential to the start of the turn. They were also designed for RNAV equipped aircraft, using the design guidelines within ICAO Doc 8168 Vol II [14] and using a minimum RNP of 1. A design speed of 280 KIAS was used to define the turn radius of the holding pattern, which is the maximum allowed speed in turbulent conditions defined for holds below 14,000 ft. In line with ICAO Doc 8168 Vol II, a design bank angle of 23° was used to determine the turn radius, taking into account a tail wind components using estimated values calculated from Eq. (3) [14]:

$$w = 2h + 47 \qquad (3)$$

where h is the altitude in thousands of feet and w is the tail wind in kts. The length of the parallel segments was calculated for a flight time of 1 min at 230 KIAS, which is the maximum IAS allowed in still air up to 14,000 ft in accordance with RNP holding design rules [12]. This equates to a true still air speed of 249.2 kts and results in a leg length of 4.15 NM.

5 The New Approaches

The proposed new approaches to runways 31 and 13 resulting from the discussed design methodology are presented in Figs. 5 and 6 respectively.

5.1 Approaches to Runway 31

For the approaches to runway 31 (Fig. 5), five IAFs have been identified, namely CEKCI for approaches from the north-east, CONAD for the south-east, ZERKI the south-west and MINDI and HARVY for approaches from the north-west, for the left-hand and right-hand downwind legs respectively. These IAFs have been located in such a way as to ensure adequate vertical separation between aircraft using adjacent arrival and departure routes whilst assuming a 3 degree descent gradient. The right-hand IAF (HARVY) is further upwind than its left-hand counterpart (MINDI) due to there being more arrival routes from the west (not shown in Fig. 5), requiring merging at a point further downwind on the left-hand circuit.

Two T-bar structures for runway 31 have been designed, one having the existent waypoint ENELO as the FAF, 5.3 NM from the runway threshold, and having the newly designed XERRI 3.14 NM further out. The waypoints PALMA, MOLLY, EREND and FARUN, all situated 5.6 NM laterally from their respective FAF, complete the T-bar structures, thus allowing for a 2.8 NM radius turn to be initiated at these waypoints to bring the aircraft aligned with the runway extended centreline at the respective FAF. The two T-bar structures have been implemented to facilitate traffic separation, in the event an extended downwind leg would be required. Indeed the outer T-bar structure results in an extension of the approach by 6.2 NM with respect to the shorter (inner) approach pattern, which, at a nominal speed of 180kts, translates to an extension of just over 2 minutes in flying time.

The north-easterly and south-westerly approaches are designed to merge with the paths of the inner T-bar structure, thus ensuring the shortest possible ground track to be flown. Accordingly, IAFs CECKI and ZERKI are followed by IFs DELLY and FERGI respectively, both situated at the apex of the base turn of the north-westerly approaches.

The south-easterly approach is straight-in, requiring no IF past the IAF CONAD, but XERRI, designed for the outer T-bar structure, also acts as the IF for this approach route.

Fig. 5 illustrates the danger zones LM-D1 and LM-D6 to the north of the airfield. These are activated by a NOTAM [2], making the right hand down wind route temporarily unavailable. This is already the procedure adopted by ATC in Malta. Likewise, when danger zones LM-5 and LM-D7, situated to the south-west of the airfield, are active, arrivals will not be allowed via ZERKI and traffic will need to be re-routed.

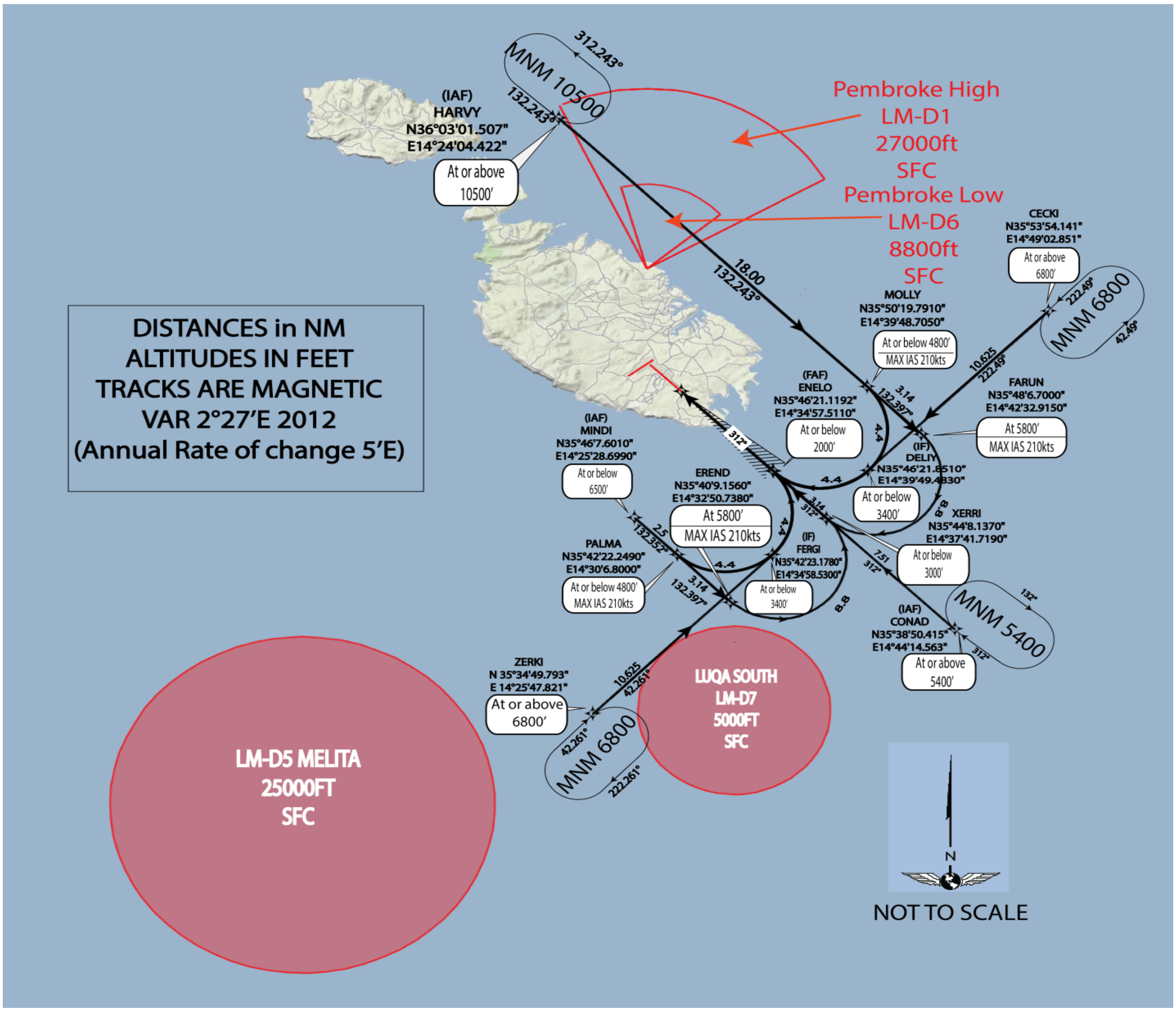

Fig. 5 The proposed revised approach routes to runway 31.

Holding patterns were placed at the IAFs, except at MINDI when runway 31 is use and DEXER when runway 13 is in use. In the latter cases, holds were designed within the STARs connecting to these IAFs. The IAFs having a holding pattern were geographically placed such as to allow aircraft to proceed to the next waypoint by maintaining a continuous descent with a glide path of 3°, equivalent to a descent rate of 320ft/NM. On the other hand MINDI and DEXER were placed 2.5NM away from the start to the RF turn. This distance was calculated using the formula for the minimum distance allowed between a fly-by turn and a fixed radius turn as specified in [12], which would allow an aircraft with an indicated airspeed of 250 KIAS to make a track change smaller or equal to 90° to intercept the track which aligns aircraft tangentially to the start of the RF turn.

5.2 Approaches to Runway 13

For the approaches to runway 13 (Fig. 6), six IAFs have been designed. These are FERRO and DEXER for approaches from the north-east, JOLLY and SERRA for the south-east (left hand and right hand downwind circuits respectively), CUBAN the south-west and QUEEN for straight-in approaches from the north-west.

Two approaches are provided for the north-east primarily so that arrivals could be routed via DEXER instead of FERRO when danger zone LM-D1 is active. In contrast with the design for runway 31, only one T-bar structure has been designed for runway 13. This is primarily because arrivals from the south are not very common and as a result it is considered that extended downwind legs will rarely be required.

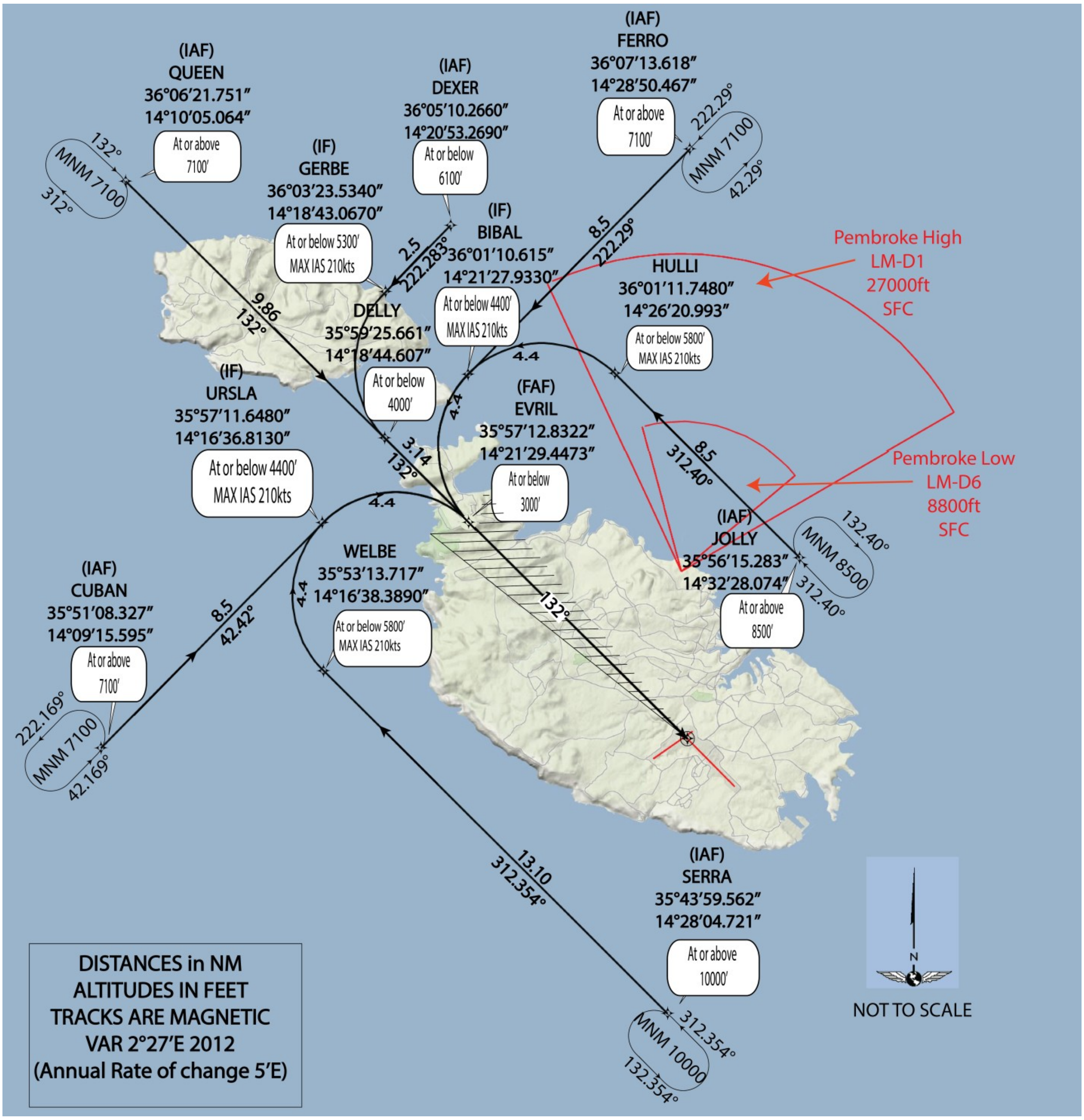

Fig. 6 The proposed revised approach routes to runway 13.

As for the approaches to runway 31, the north-easterly and south-westerly approaches have been designed to merge with the paths of the T-bar structure, thus again ensuring the shortest possible ground track to be flown. Accordingly, IAFs KUBAN and FERRO are followed by IFs URSLA and BIBAL respectively, both situated at the apex of the base turn of the south-westerly approaches. The IF GERBE follows the IAF DEXER.
Holding patterns were again placed at the IAFs, except at DEXER.

6 The EKOLA 1A STAR

The analysis presented in this paper focuses on arrivals from the EKOLA entry point, landing on runway 31 after flying a right hand downwind leg over the eastern coast of the island from HARVY to MOLLY, turning in to fly by the IF DELY and intercepting the ILS from the right. Consequently, this paper also presents a proposal of the EKOLA 1A STAR, (Fig. 7). From EKOLA, a track of 137.6° (Magnetic) leads directly to the HARVY IAF, 34 NM away. Combined with the HARVY approach via DELIY (ie: using the inner T-bar structure), the EKOLA 1A STAR results in 65.37 track miles (NM) from the entry point to the runway threshold.

7 Quantification of Gains

Quantification of the economic and environmental gains that can be achieved with the introduction of the proposed procedures can only be performed against a reference baseline. The reference baseline chosen was the actual paths taken by aircraft flying in via EKOLA and landing on runway 31 via a right-hand downwind leg. To this extent, the Kinetic SBS-3 ADS-B receiver, which decodes ADSB transmissions transmitted on Mode-S (1090MHz) was used to log the trajectories flown by aircraft as they approached the runway to land. This allowed the reconstruction of the trajectories flown by each aircraft logged which, in turn, enabled the determination of the track miles of each trajectory flown. The ADS-B receiver used has a coverage range of 200 NM, making it suitable to analyse the descents from the top of the descent (TOD) point down to the moment of touchdown. The ADS-B receiver outputs a data stream of the decoded Mode-S signal, including the aircraft call sign, altitude, ground speed, track, latitude, longitude, vertical rate, squawk code and a flag that indicates whether the aircraft is airborne or otherwise. The receiver outputs the data stream for each aircraft at a base rate of, on average, 1Hz.

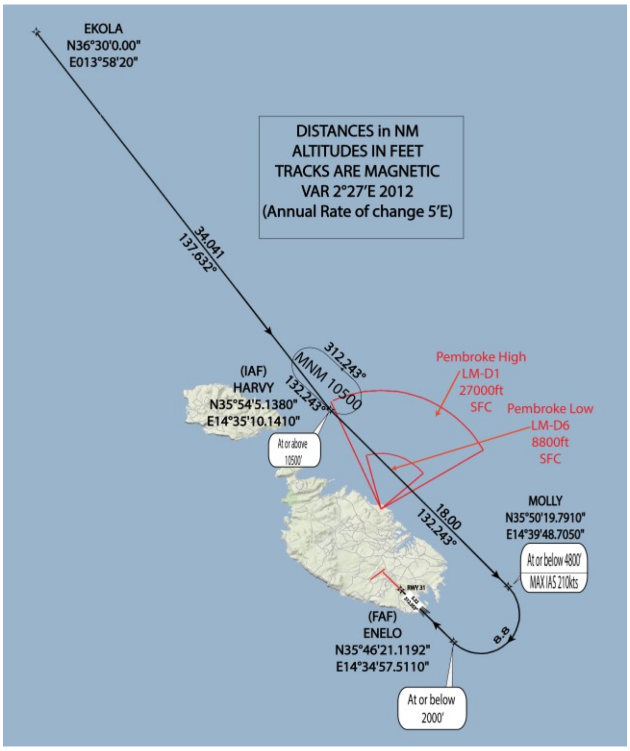

Fig. 7 The proposed EKOLA 1 STAR and arrival route for runway 31 via HARVY and DELIY (not shown).

The data stream was processed with software developed in JAVA and this facilitated the organisation of the recorded trajectories into separate files held within folders for each day. Lateral profiles are reconstructed using the logged geographic location given by the latitude and longitude, while vertical profiles are reconstructed using the recorded altitude and timestamp.

The constructed trajectories were then processed in Matlab®. Processing included filtering of data, which was necessary due to ADS-B transmission outages and other log discontinuities that resulted in unusable records. As the ADS-B receiver receives transmissions of all aircraft, the filtering also facilitated discrimination between aircraft approaching LMML and all other traffic, including en-route aircraft and aircraft outbound from LMML. In order to reduce memory space and processing time, the ADS-B logs were then reformatted so that successive records were only stored if the aircraft track changed by half a degree, as intermediate points proved redundant.

Analysing the logged trajectories, it became evident that aircraft often do not overfly the entry points, but tend to fly past them, often having a lateral displacement of several miles. In the new proposed STAR, however, it is assumed that the aircraft will overfly the entry point EKOLA. Consequently, it was necessary to ‘normalise’ the recorded trajectories so that a fair comparison in track miles flown could be made with the EKOLA 1A STAR. This normalisation involved identifying, for each logged flight, the point where the base turn started and this was used as the centre of a circular arc that passed through EKOLA. Then, the start of the arrival for the recorded flight was taken to be the intersection point between this arc and the actual trajectory flown. This effectively generated an arrival path equal in length if the aircraft had actually flown over EKOLA. Thus a fair comparison between the track miles flown in the proposed new STAR EKOLA 1A (65.37 NM) and the logged flights could be made.

The baseline trajectories from each entry point were plotted to display the lateral profiles flown by logged flights, as seen in Fig. 8. Trajectories that were identified to have followed a longer route due to lateral vectoring or having flown a hold pattern were discarded, as this would have skewed results. Trajectories that were identified to exhibit any errors, including offsets in the reported positions were likewise considered as outliers and discarded. Trajectories that exhibited gaps in the timestamp were further scrutinised and their correct trajectories were reconstructed only if the time gap between the records occurred at altitudes above 10,000 ft. Otherwise they were discarded. This was done because it could be fairly assumed that above 10,000ft, the aircraft would be flying at constant CAS, allowing the fuel burn to be correctly estimated.

8 Results and Discussion

The analysis included in this paper is based on trajectories recorded from the 22nd of March until the 24th of June 2013. From the trajectories recorded, 135 arrivals from EKOLA landing on runway 31 via a right-hand downind leg were extracted and these baseline trajectories were plotted as seen in Fig. 8. The associated track miles flown were also calculated for each trajectory. On no flight was any danger zone active and all flights flew direct to REKSI, the current RNAV waypoint that forms part of the T-bar structure for the approach to runway 31 (Fig. 1). The variation (dispersion) in the paths followed by aircraft is clearly visible in the trajectories plotted in Fig. 8. This is also captured in the histogram of the track miles flown (Fig. 9), which indicates the number of track miles that could have been gained had the aircraft followed the proposed EKOLA 1A STAR and HARVY arrival route. The variaiton in paths is primarily associated with the fact that there are no established arrival routes leading to the T-bar approaches and aircraft follow trajectories at the flight crew’s discretion .

Of the 135 normalised flights recorded, 74 (54.8%) exhibited a longer trajectory than the proposed new STAR EKOLA 1A, indicating that savings could be made with the introduction of the new procedure. The remaining flights will have flown tighter base turns, as evidenced in Fig. 8. It is probable that visual approaches would have been made on these flights, a common practice in Malta, given the extent of good weather the island enjoys. This, naturally, allows pilots to fly with less leeways than standard instrument approach procedures allow for, and naturally distracts from the overall gains that can be achieved. However, for optimal descent approaches, the track miles to be flown need to be known prior to top of descent in order to plan the vertical profile too besides the plan path. Given that the proposed procedure results in the shortest track miles path that can be formally published to ensure safe operation in all expected operating conditions, it does offer savings and improvement over current procedure. Furthermore, it is not envisaged that OPDs will be operationally planned based on visual approaches that fly tighter base turns than those published.

The shortest normalised recorded trajectory had a total of 57.3 track miles (NM) to the runway threshold, 8.1 NM shorter than the proposed route. The longest was 79.9 NM, 14.6 NM longer than the proposed route. When all paths were analyzed, the average track miles flown were found to be 66.9 NM, 1.5 NM more than the proposed trajectory. This means that, if all flights were to follow the proposed new route (EKOLA 1A STAR and the HARVY approach via DELEY), an average of 1.5 NM on each flight would be saved.

Assuming that flights flying shorter tracks than the proposed STAR and approach were flown under VFR (61 of the 135 recorded flights), these would probably also not have followed the proposed route once operational and another analysis can be made with these flights ignored, focussing only on those flights that would have benefited from the new procedure. Results show that these latter flights flew, on average, 70.57 track miles. This means that these flights would, on average, benefit from a 5.2 NM reduction in the total track miles flown had they followed the new proposed route.

The vertical profiles of the recorded flights were also generated from the recordings and these are plotted in Fig. 10. Aircraft that exhibit a longer trajectory than the new proposed procedure appear to have a tendency of arriving higher than those trajectories that flew shorter trajectories. This is reasonable, as aircraft that remain high for any reason will need to extend their flight path to intercept the glideslope correctly. This extension is typically implemented in the form of an extended downwind leg.

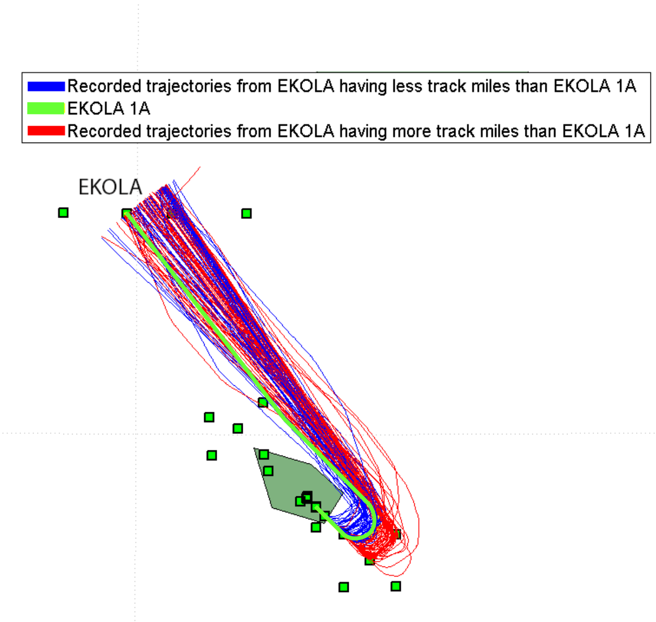

Fig. 8 Recorded trajectories over the period 22nd March 2013 to 24th June 2013 and the proposed new EKOLA 1A STAR and HARVY arrival route.

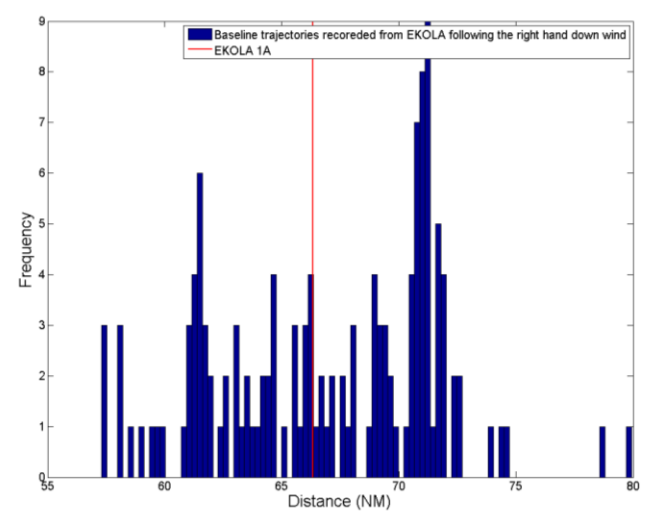

Fig. 9 Histogram of the total track miles flown in the recorded trajectories arriving from EKOLA (22nd March 2013 to 24th June 2013).

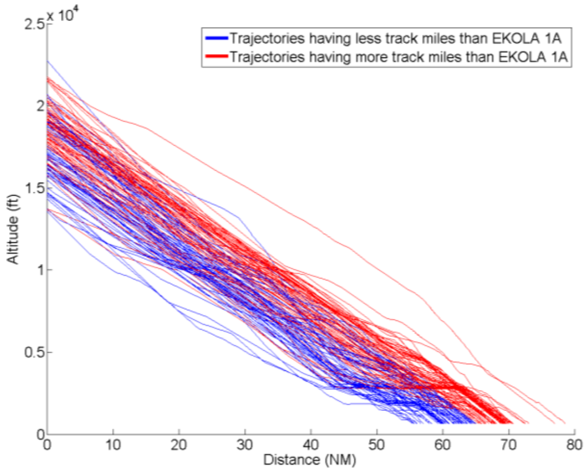

Fig. 10 The vertical profiles of the recorded trajectories arriving from EKOLA (22nd March 2013 to 24th June 2013).

Whilst Fig. 10 indicates that there are a number of flights that descended early to have segments of shallow glides or level flight whilst others that have had stepped descents, for the purpose of the quantification of gains in terms of fuel burn (and ensuing CO_2 emissions), it was assumed that the extra track miles were flown at cruise altitude. Whilst this simplified the assessment, it results in conservative estimates, as flying at lower altitudes would result in higher fuel burn. As a comparison, the analysis was repeated with the assumption that all the extra distance was flown at 3,000ft which, of course, then resulted in optimistic forecasts of savings.

Since the logged trajectories did not contain information on aircraft type, gains had to be calculated using the fuel consumption of a typical aircraft. Single aisle aircraft the size of the Airbus A320 and Boeing 737 families constitute the large majority of the traffic flying in and out of Malta and conseqeuntly the A320 was chosen for the analysis. To this extent, the BADA Revision 3.7 performance files of the A320 with CFM-56 engines at nominal weight (64,000kg) were used for all calculations.

The histograms of the potential fuel savings that could have been achieved by the 74 flights were the extra track miles not flown are shown in Fig. 11 and Fig. 12.

In Fig. 11, results are based on the assumption that the savings were achieved at cruise level. The calculations have been made using the ground speed recorded on each flight, which allowed the estimation of the reduction in flight time that would have resulted had the flight been flown on the proposed STAR/arrival route combination. Using the fuel flow data for cruise from the BADA performance files, the total fuel that would have been saved was then calculated for each flight.

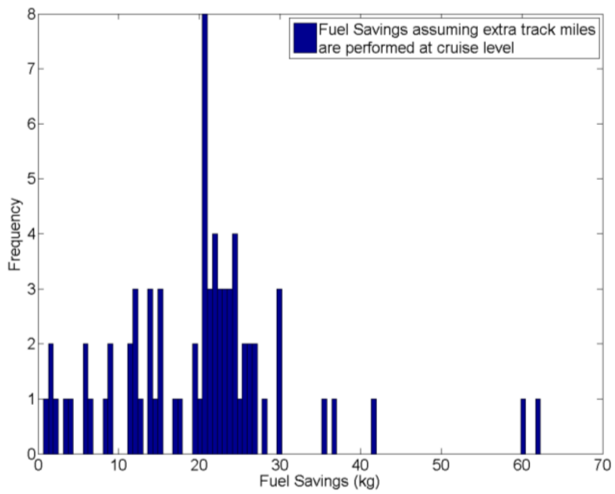

Fig. 11 Histogram of the potential fuel savings of the recorded flights, assuming that the reduction in track miles is gained at cruise level.

In total, for the 74 trajectories that could have benefited from the shorter suggested route, 1,487 kg of fuel would have been saved if the extra distance was not flown at cruise level. This corresponds to an average saving of 20.1 kg per flight. Given that 3.15 kg of CO_2 are produced for every 1kg of jet fuel burned [15], every flight, on average, would then have benefited from a reduction of 63.3 kg of generated greenhouse gases.

Fig. 12 shows the histogram of the same analysis were the savings in track miles flown to be made at 3,000 ft.

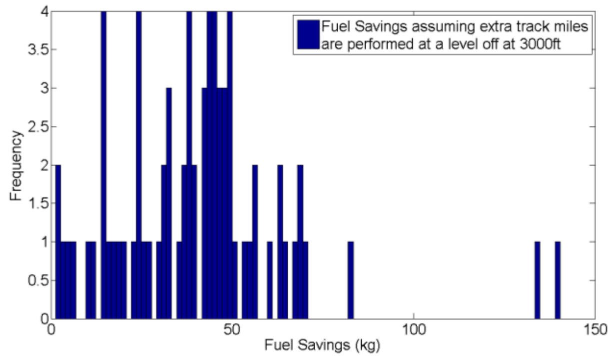

Fig. 12 Histogram of the potential fuel savings of the recorded flights, assuming that the reduction in track miles is gained at 3,000 ft.

In total, the same 74 flights would have benefited from a reduction of 2,991 kg in fuel burn, which corresponds to an average saving of 40.4 kg per flight. This, in turn, corresponds to an average reduction of 127.3kg of CO_2 generated per flight.

Using these results, it is interesting to consider the total impact the introduction of the EKOLA 1A STAR used in conjunction with the proposed arrival routes for runway 31 could have on all traffic. In an unpublished study carried out by the authors, it was found that about 40% of all traffic tend to arrive from EKOLA and land on runway 31. Taking the 135 trajectory records logged in this study as typical, 54.8% of all flights could be expected to benefit from a reduction in track miles flown. Considering then that Malta International Airport experiences just under 20,000 arrivals of scheduled and un-scheduled flights (ie: excluding general aviation) annually [16], it can be expected that around 4,200 flights would benefit from the proposed new route annually. This would amount to a total fuel saving of the order of 85 tons were the gains made at cruise altitude, corresponding to a saving of over 250 tons of man-made greenhouse gases annually. Were the savings to be exploited from 3,000 ft, the corresponding values would be about 170 tons and 530 tons respectively. This, of course, assumes no further gains due to the introduction of OPDs, which is where the major gains can be expected to be achieved.

9 Conclusion

This paper presented, at a strategic level, a proposal for revised approach routes for the main runways (31 and 13) at Malta International Airport (LMML). These approach routes have been designed to allow aircraft to fly the shortest possible routes into Malta, with the intention of increasing the repeatability of the path followed by the aircraft over current levels, thus ultimately leading to reduced fuel burn and emissions. To achieve this, fixed radius (RF) turns were used for base turns, whilst TF turns were allowed where heading changes of less than 90° were required.

In order to obtain an indication of the improvement the new proposed routes could be expected to bring about, an experiment was designed in which trajectories of actual flights arriving from the north-west (via EKOLA) were recorded using an ADS-B receiver and compared to the the standard track of the new proposed route. The analysis focused on the amount of track miles reduced and associated reduction in fuel burn and CO_2 emissions that could be expected were the inbound aircraft to follow the route proposed in this work. The results show that a small but significant gain can be achieved. Greater benefits can, of course, be expected with the implementation of ODPs in conjunction with the proposed route and this work lays the foundations to facilitate aircraft to accurately plan such profiles as a step towards greater gains in the reduction of fuel burn and CO_2 emissions in the approaches to Malta International Airport.

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