I. INTRODUCTION

Manned aircraft operations are typically conducted under Performance Based Navigation (PBN) [1] and Performance Based Communication and Surveillance (PBC&S)[2]. These concepts implicitly embed aircraft performance requirements on communication, navigation and surveillance (CNS) capability. As a result, there exists a trade-off where, for example, poorer navigation performance can be offset by more stringent communication and surveillance performance to allow sufficient time for ATC intervention. Underpinning these concepts are a set of separation standards that collectively ensure safe routine operations. Such separation standards and associated CNS performance requirements have not yet been developed for unmanned aircraft (UA), yet will be required to safely scale unmanned operations within an Unmanned Traffic Management (UTM) system.

The PBN concept is based on the foundations of Area Navigation (RNAV) systems that aims to ensure global standardisation of RNAV and Required Navigation Performance (RNP) specifications. These specifications for manned aircraft consist of requirements on accuracy, integrity, continuity, and functionality in lateral navigation capabilities. This obviates the prescription of specific technology and services for navigation in a PBN environment, giving flexibility to operators to select any combination of technology and services that meets the performance requirements. A similar flexibility is desirable in unmanned operations, where rapid technological progress means there may be multiple approaches to safe navigation. Furthermore, the established RNP specifications in manned aviation provide a good basis for developing similar specifications for UA.

Fig. 1: Flight path at Kallang offices for capturing navigation performance data

The development of RNP specifications for UA requires flight trials to establish real-world navigation performance, as well as identifying factors which may affect navigation performance particularly in urban environments. The flight trials which this paper analyses to investigate the navigation performance of UAS for developing RNP specifications were conducted by Nova Systems as part of a broader research and development effort.

Nova Systems currently leads a consortium of partners developing a UTMS for the densely populated Singaporean metropolitan environment. This effort has attracted matched funding from the Singaporean government. In their initial proposal to the Singaporean Ministry of Transport, Nova pinpointed a number of challenges which need to be addressed including uncertainty around regulation for UTM airspace, platforms performance and reliability, access to critical data, and a completely different CNS architecture. With support from their partners, who include Scout Aerial, AGI, M1, Rohde and Schwarz, and Amazon, Nova has been conducting a suite of R&D activities and flight trials. This includes examination of CNS principles in supporting the design of a UTM airspace traffic network for Singapore, alongside flight trials capturing performance statistics of 4G networks and navigation performance.

This paper details the flight trials conducted to capture lateral and vertical navigation performance measurements of select UA. In particular, the contributions of this paper are:

- flight trial lateral and vertical navigation performance results and example RNP derivations for two multi-rotors in terms of their lateral navigation accuracy
- observations and recommendations with regards to meaningful and accurate measurement of the navigation performance of UAS operated in urban environments
II. BACKGROUND

No definition for RNP in the context of UTM exists yet. The existing RNP specifications for manned aircraft are typically labelled as RNP-X after the corresponding accuracy requirement, which mandates that the aircraft must remain within ±X nautical miles (nmi) of the centre of the track 95% of the time. An RNP AR APCH (authorization required procedure) in manned aviation can be as low as RNP-0.1[3], which is still too large for UA operation especially in urban areas¹. Furthermore, suitable specifications for integrity, continuity and availability will need to be established for UA. Finally, RNP only specifies the requirements on lateral navigation performance, neglecting any along-track performance² and vertical navigation performance. Vertical navigation performance is partly included in some RNP procedures, such as RNP APCH where the vertical deviation limit is specified as 22 m. Explicit inclusion of total along-track performance however requires first that the trajectory is defined in four dimensions (including time) which is also known as Trajectory Based Operations (TBO). Such an extension into four dimensions for manned aircraft has been explored[4], however it has yet to be fully implemented in practice. TBO in manned aviation has initially been partially implemented by Required Time of Arrival (RTA) functionality which supports setting a time of arrival for waypoints that the aircraft must meet. However, for the UAS platforms tested no such functionality exists. Only a speed for the mission can be set, which the aircraft attempts to maintain, with no regard for when it arrives at each waypoint. Without an RTA-like feature, it is meaningless to consider along-track RNP in detail for UAS and thus it is not considered in this paper.

The RNP accuracy requirement described earlier is currently only defined in the lateral dimension as a constraint on the shape of the Total System Error (TSE) distribution of the aircraft. The TSE distribution captures the true position offset probability of the aircraft from its intended track, and is typically represented by a Laplace distribution in manned aviation [5]. The TSE encapsulates three error components. The first of these is Path Definition Error (PDE) which captures the difference between the desired flight path and the user defined flight path. This error is typically considered to be negligible in manned aviation with independent verification. Flight Technical Error (FTE) is measured as the difference between the flight path of the user and the flight path estimated by the navigation system on the aircraft. It captures the control system’s ability to follow the set flight path, as well as any other physical effects that cause the aircraft to deviate from its flight path. In essence, the FTE is the deviation from the intended track that is known by the aircraft’s control system and which it is actively trying to minimise. The accuracy of the positioning solution of the aircraft is captured by the Navigation System Error (NSE), which is the difference between the path estimated by the aircraft and its true path as determined from some ground truth source. The relationship between these error types can be seen in Figure 2a.

Whilst not yet explicitly included in RNP, the vertical navigation performance will likely be included in future and could be quantified through a similar set of error distributions as for the lateral navigation performance. Similar to TSE, the aggregate error is termed Total Vertical Error (TVE), and is defined as the difference between the true altitude of the aircraft and its desired altitude. One of the components of TVE is the Assigned Altitude Deviation (AAD) which is analogous to FTE as the difference between the estimated altitude and the assigned altitude. The Altimetry System Error (ASE) is the second major component of TVE which quantifies the accuracy of the altitude estimation system as the difference between the true altitude and the estimated altitude. Similar to the lateral case, a Path Definition Error may also be present, where the assigned altitude of the aircraft differs from the altitude the aircraft is supposed to be at (the desired altitude). The relationship between these errors is show in Figure 2b.

Navigation performance of UA in terms of lateral and
vertical error has not been quantified extensively in the literature. The FTE, NSE and TSE of a MikroKopter Okto XL 6S12 was assessed in [6], where the 1-sigma TSE ranged between 1-6 metres across the flight paths. However, the distributions of the errors were not explicitly mentioned, and only the RMS values were discussed. Some simulation results for a small vehicle flying straight line trajectories in the presence of wind near buildings was analysed in [7], where the RNP accuracy value was found to be about two metres in winds up to 6 m s⁻¹.

III. FLIGHT TRIAL SETUP

A. Positioning Solution

Analysis of NSE and TSE require a source of ground truth positioning data for the aircraft. In indoor environments, technologies such as Vicon and Optitrack can reliably yield positioning errors less than 2 mm [8] and 3 mm [9] respectively. Outdoors however, a different positioning system is needed. Most outdoor positioning systems are based on GPS, such as Differential GPS which yields positioning accuracy of around 1 m to 3 m [10]. However, more accurate positioning solutions utilising carrier-based ranging exist. Real-Time Kinematic (RTK) and Post-Processed Kinematics (PPK) utilise a base station on the ground that can provide corrections to the position of the RTK rover onboard the aircraft. The primary difference is that RTK is employed in real time to improve the navigation ability of the aircraft, whereas PPK is conducted after the mission and allows adjusting various settings that can improve the quality of the positioning solution.

RTK/PPK yield up to centimetre-level accuracy, which in practice translates to about 2 cm of horizontal error and 3 cm of vertical error [11]. The accuracy of RTK on-board a quadrotor at altitude was specifically examined in [12], where a horizontal accuracy of 2 cm and a vertical accuracy of 1.2 cm were obtained at an altitude of 33 m. The use of RTK/PPK for UAS mapping of forested areas was explored in [13] which suggested RMS errors of 2.6 cm and 3.5 cm in the horizontal dimensions and 8.2 cm in the vertical dimension.

One of the downsides to RTK/PPK is that it is affected by satellite occlusion similar to normal GPS. A positioning solution requires at least five visible satellites for position fixes and solution quality reporting (or at least six when using two constellations). However, when this failure mode occurs it is very likely the aircraft itself cannot use GPS either and thus cannot be flown in automated mode for gathering navigation performance data anyway. Another downside is that whilst RTK/PPK positioning methods correct for satellite clock errors, orbit errors, and ionospheric and tropospheric delays, they are still affected by multipath effects. When using PPK, the solution reports its accuracy which indicates whether it is at centimetre-level, sub-metre, or metre-level accuracy. This can be used to cull any flight data where the accuracy isn’t adequate to limit the effects of multipathing or satellite occlusion on the accuracy of the analysis.

The determination of vertical navigation performance requires accurate vertical positioning data. The PPK solution will be used to provide the ground truth altitude data about the vehicle’s height, however there are some key considerations with this choice. Firstly, the use of GPS for altitude information is not common. Typically, the vertical accuracy of a standard GPS receiver is in the order of metres. In manned aviation, barometric pressure is used to represent altitude which is appropriate for vertical separation. For UAS however, vehicle altitude measurement is not consistent, which can cause issues during flight trials involving multiple UAS operators and vehicle types [14]. The altitude is often represented relative to the take-off location with GPS-based systems, which makes comparing altitudes for aircraft that took off at different locations unreliable. Whilst the vertical navigation performance can be evaluated without worrying about this, the eventual vertical separation of UAS will require a homogenisation of altitude referencing.

B. Flight Configuration

The flight trials conducted employed two multirotor platforms: a DJI M600 and a DJI Phantom 4 Pro. The M600 is a large hexacopter with dimensions of 1668 mm by 1518 mm by 759 mm and weighs 9.1 kg with a maximum take-off weight of 15.1 kg [15]. The unit used in the trials was equipped with the A3 Pro flight control system, which includes three GPS and IMU units. The Phantom is a smaller quadcopter, with a diagonal size of 350 mm without propellers, and weighs 1380 g [16]. The stock flight control system was used in the trials, which uses one GPS receiver and two IMUs. A single-band Emlid Reach M+ RTK rover was attached to both vehicles to capture data for the PPK positioning analysis to explore whether the different vehicles exhibited different navigation performance.

The navigation performance data was captured from flights conducted as part of a larger set of flight trials by Nova Systems with multiple objectives. As such, only a subset of the flights were appropriate for navigation performance considerations. From this subset, only a small number were used for the analysis in this paper to ensure reliable and meaningful data (see Section IV for further information on why flights were discarded). In total for the M600, seven flights for navigation performance data are analysed with a combined flight time of 1672 seconds of which 1095 seconds was during the longest flight. For the Phantom, 663 seconds of flight time was recorded over the three flights that are analysed. The flights that passed the data processing stage in the next section were conducted at four different locations in Singapore:

- an open field surrounded by buildings and trees in One North (five M600 flights and two Phantom flights)
- a transit over a river in a riverside park at Kallang (one M600 flight)
- one flight in a parking lot surrounded by buildings near the Nova Systems office in Kallang (one M600 flight, see Figure 1 for the flight path)
• one flight in a field near the Nova Systems office in Kallang (one Phantom flight).

The flights were flown in automated mode, so as to focus the assessment on the capabilities of the platforms rather than those of the pilot. Furthermore, the cornering mode for the aircraft was set to Straight, which causes the aircraft to stop at each waypoint before continuing its path. Using the alternative Curved mode would result in the aircraft flying a curved path through the waypoints, which would guarantee some lateral error at each turn because the desired path of the aircraft consists of straight line segments. Thus, having the aircraft stop at each waypoint removes the unmodelled error from curved waypoint flight, at the cost of a less realistic flight trajectory and with the caveat that future trials will need to be established to investigate lateral navigation error performance on curved paths.

IV. DATA PROCESSING

The data from the on-board RTK rover was extracted and a positioning solution was found using RTKLib [17] using the rover data gathered during the trials, and base station data from the Singaporean Satellite Positioning Reference Network [18]. The estimated position of the aircraft was extracted from the flight logs (using the position estimated by the aircraft from IMU and GPS data), with the PPK solution used as the true position of the aircraft, and the waypoints sent to the aircraft used as the desired path.

In the analysis, the take-off and landing phases were neglected. During the trials, the aircraft was not necessarily placed directly on the take-off waypoint which resulted in the aircraft taking off with an existing offset, which it would only correct after it reached altitude. As such, the lateral error whilst the aircraft was rising is affected by the offset, and cannot be used for meaningful analysis. For the landing phase, the landing was often conducted manually, so it was also removed from consideration for this analysis.

Path Definition Error (PDE) was assumed to be negligible in the analysis. For most of the flights, the waypoints were generated by a routing program from which the waypoint locations were exported directly into the software used to upload the coordinates to the aircraft. For some flights where the coordinates of each waypoint were manually entered, the desired path was taken as those waypoints that were uploaded to the aircraft, so the desired path was guaranteed to be in agreement with what was actually uploaded to the aircraft. In this way, the PDE was made zero by design.

The FTE and TSE were calculated by finding the minimum absolute perpendicular distance of the aircraft from the desired flight path at each position (flight log data for FTE and PPK data for TSE). The direction of the error was kept, such that positive values denote errors to the right of the track and negative ones to the left. The NSE was then calculated by subtracting FTE from TSE.

During the flight trials and data processing, several issues were encountered. Firstly, for some of the flights the PPK solution as reported by RTKLib was found to be of low quality, such as in Figure 3. The flight path viewed from top down is shown colour-coded, with the mostly yellow path corresponding to sub-metre accuracy, and the few green sections corresponding to centimetre-level accuracy. This suggests the PPK solution cannot be trusted for centimetre accuracy positioning data for this flight, which was conducted in extreme proximity to tall buildings at the center of a corridor approximately 10 m to 15 m in width. As such, these flights cannot reliably be used to determine NSE and TSE, and were thus not used for further analysis. Furthermore, the aircraft also refused to fly in automated mode due to no GPS lock at this location. Combined, these suggest issues with UAS operation in urban environments and with measuring the navigation performance, especially between buildings. If the aircraft is unable to be flown in automated mode in such an environment, the measurement of FTE becomes meaningless for automated operations. Due to PPK sharing the same multipath and satellite visibility failure modes as the GPS on the aircraft, the NSE cannot be reliably measured either in these situations.

With an alternative ground truth positioning system, it would be possible to measure NSE even if the aircraft had to be operated manually due to lack of GPS lock. However, buildings affect the wind flow in various ways, including the speed and turbulence of the wind depending on the geometry and relative positions of the buildings in an urban environment[19] which will impact on the FTE measurement. Thus, to realistically measure TSE in urban environments close proximity to buildings, it is necessary to have both a positioning system that is not affected by building occlusion of satellites, as well as an aircraft that can fly in automated mode without proper satellite visibility (using e.g. a fallback inertial navigation system). Otherwise, aircraft relying on GPS will need to be limited to flight paths that do not suffer from significant occlusion and multipathing effects.
V. RESULTS & ANALYSIS

A. Horizontal Error Distributions

An example of the resulting FTE, NSE and TSE data for one of the M600 flights is shown in Figure 4, plotted with the number of visible satellites. The data shows that the TSE predominantly tracks the NSE, with the FTE staying relatively constant in comparison.

The lateral navigation performance distributions for the DJI M600 can be seen in Figure 5, and likewise for the DJI Phantom 4 Pro in Figure 6. For each, a normal and a Laplace distribution are fitted with their location and scale parameters listed and the sum of square errors (SSE) given as an indication of the relative accuracy of the fit.

Figures 5a and 6a for the M600 and Phantom respectively show that the FTE for both platforms is captured best by a Laplace distribution, with the M600 having approximately half the scale parameter suggesting less variance in its lateral FTE performance presumably due to more control authority. For both aircraft, the FTE is biased to the right of the track with a mean of approximately 0.12 m. For the Phantom, the FTE has extra peaks at about 4 m and −6 m, however as only a few flights were conducted it these are likely outliers that may only appear significant. It is worth noting that because the flights were conducted in low wind conditions, the FTE results are only applicable to low wind operation and is not representative of the FTE across all conditions. Real operations will require assessment of FTE across the full spectrum of environmental conditions, particularly in various wind conditions.

The NSE distributions for the M600 in Figure 5b and for the Phantom in Figure 6b show much more variation than the FTE, where the M600 has a Laplace scale parameter of 0.79 m, and the same for the Phantom is 0.61 m. The true NSE distribution is asymmetrical particularly for the M600 which also has a significant mean of 0.51 m. These factors suggest that the NSE plays a more significant role than the FTE in the Total System Error of the aircraft when wind is not a significant factor. The NSE results presented have a dependence on the locations where the flights were conducted, as the geometry of the surrounding buildings and landscape affects the visibility of satellites and the accuracy of the positioning solution. As such, the results are mainly valid for flights in conditions where the nearest buildings are several tens of metres away on average. Further navigation data capture should be conducted in a larger variety of locations to remove biases from any one location on the NSE distributions.

The TSE distributions are presented in Figures 5c and 6c for the M600 and Phantom respectively. For both platforms, the SSE of a Laplace and a normal distribution is very similar. However, the Laplace distribution is typically used due to it being more conservative, as the raised tails give more probability mass to gross navigation errors. In terms of the TSE, the M600 has a mean closer to zero, with a smaller scale parameter, suggesting it navigates better overall than the Phantom.

B. Vertical Error Distributions

The vertical error analysis was only conducted for the M600, as there were not enough Phantom flights for which high quality data could be obtained. For the M600, the AAD results are only available at a precision of 10 cm, which corresponds with the precision of the altitude reported by the aircraft.

The AAD for the M600 is shown in Figure 7a. The AAD distribution is very compact, suggesting the aircraft is accurate at maintaining the assigned altitude. The ASE distribution however, shown in Figure 7b, exhibits multi-modal mixture components. Table ?? shows the parameters for fitting a Laplace distribution onto each flight. Excluding Kallang Offices, the scale parameter is very consistent between the other flights, with the mean showing most of the variation. Thus, the ASE distribution can be considered to consist of the sum of multiple Laplace distributions with the same scale parameter but different means, which gives rise to the multi-modal behaviour. This suggests that the altitude estimation of the aircraft for a given flight might be represented by a Laplace distribution with a scale parameter 0.09 to 0.15, with a constant offset in the mean. The Kallang offices flight does not fit this interpretation, as it has a much larger scale parameter. Detailed information about this flight is shown in Figure 8, where the top left plot shows that the ASE and TVE over time stays mostly below zero until about 1500 seconds into the mission where it switches to mostly above zero. This results in the bimodal ASE distribution shown in the bottom left plot. The primary difference with

| TABLE I: Parameters of the fitted Laplace distributions over the ASE distribution for each flight of the M600 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Kallang Offices | Mean (m)        | Scale (m)       | Mean (m)        | Scale (m)       | Mean (m)        | Scale (m)       |
| Kallang Offices | -0.12           | 0.47            | 0.97            | 0.09            | 0.70            | 0.14            |
| One North 1     | 0.37            | 0.14            | 1.40            | 0.10            | 3.37            | 0.12            |
| One North 2     | 0.37            | 0.14            | 1.40            | 0.10            | 3.37            | 0.12            |
| One North 3     | 0.93            | 0.15            | 3.37            | 0.12            | 3.37            | 0.12            |
| One North 4     | 0.93            | 0.15            | 3.37            | 0.12            | 3.37            | 0.12            |
| One North 5     | 0.93            | 0.15            | 3.37            | 0.12            | 3.37            | 0.12            |
this flight other than its length is that its flight path, shown in Figure 1, consists of multiple altitude levels. Thus, it seems that the altitude that the aircraft is operated at may affect the mean of its ASE distribution, with lower altitudes resulting in the altitude estimate undershooting the true altitude, and overshooting for higher altitudes. More flight trials need to be conducted however to verify this effect, and ensure it is not an artifact of using PPK altitude as ground truth data.

C. RNP Specifications

The RNP specifications for manned aircraft define an accuracy requirement represented by a 95% bound on the TSE. This accuracy bound can be calculated from the TSE distributions of the platforms, which are assumed to follow a Laplace distribution. Then, the B\% accuracy bound at \( b \) for a Laplace distribution with zero mean is given by,

\[
B = \int_{-b}^{b} \frac{1}{2a} e^{-\frac{|x|}{a}} dx
\]

where \( a \) is the scale parameter of the distribution. This can be rearranged to solve for the bound \( b \), such that \( B \) percent of the probability mass of a zero mean Laplace distribution is contained in \((-b, b)\):
Unlike in manned aviation, the TSE distributions of these UA platforms have a mean that is of the same order of magnitude as the scale parameter. Thus we must explicitly include it when determining the 95% accuracy value. As the mean \( \mu \) simply shifts the distribution, it similarly shifts the 95% accuracy bound, which gives us the accuracy value \( X \),

\[
X = -a \ln(0.05) + |\mu| \tag{3}
\]

where the absolute value of the mean \( \mu \) gives the worse accuracy value between the negative and positive side of the distribution. This is done because the accuracy value assumes a symmetric distribution, and thus taking the accuracy value that is further from zero guarantees that the TSE distribution can meet that accuracy value on both sides.

On-board performance monitoring and alerting is also mandated by manned RNP specifications. The system must provide an alert if the accuracy requirement described above is not met, or if the probability of exceeding two times the accuracy value is greater than \( 10^{-5} \) \[1\]. Whilst this second requirement does not explicitly require the aircraft to stay within 2\( X \) of the center of its track 99.999% (i.e. \( 10^{-5} \)) of the time, this is needed in practice as otherwise the aircraft would be constantly alerting. The platforms tested do not estimate the FTE, NSE or TSE distributions in real time and thus have no alerting capability regarding the navigation performance, meaning a static TSE distribution must be used which does not exceed the alerting accuracy requirement. Thus, the accuracy value \( X \) is re-derived from this second monitoring requirement using (2), which yields,

\[
X = \frac{-a \ln(0.00001) + |\mu|}{2} \tag{4}
\]

This will always be a stricter requirement than the 95% accuracy bound when a Laplace distribution is used. See the appendix for RNP accuracy value calculations when assuming a normally distributed TSE.

### VI. CONCLUSIONS

The flight trial results suggest that UAS operations in urban environments very close to buildings are likely to have significant difficulties in navigating. Furthermore, the navigation performance in these situations cannot be meaningfully evaluated, as the aircraft cannot fly in automated mode due to insufficient visible satellites, and PPK positioning is not reliable for the same reason. When UAS operations are conducted sufficiently far from buildings to avoid satellite occlusion issues, the navigation performance is good. The DJI M600 was found to meet an RNP accuracy value of at best 4.32 m and the DJI Phantom 4 Pro a value of at best 5.07 m in the no or low wind conditions tested assuming a Laplace distribution for the navigation error. This suggests good performance in low wind conditions, however realistic wind conditions will result in higher RNP accuracy values. Nevertheless, it is hoped that these results shed some light on the real-world navigation performance of small multi-rotor UAS, and encourage further data capture to support the development of unmanned RNP specifications.

### APPENDIX

When the TSE is modelled by the normal distribution, the 95% accuracy value can be calculated with,

\[
X = \sigma \sqrt{2} \text{erf}^{-1}(B) + |\mu| \tag{5}
\]

| TABLE II: RNP accuracy values for the two platforms using both the Laplace and normal distributions |
|-----------------------------------------------|
|                                | M600 | Phantom 4 Pro |
|-----------------------------------------------|
| 95% accuracy value (Laplace)                  | 2.34 | 2.98          |
| 95% accuracy value (normal)                   | 1.97 | 3.33          |
| 99.999% accuracy value (Laplace)              | 4.32 | 5.07          |
| 99.999% accuracy value (normal)               | 2.91 | 3.58          |
where \( \sigma \) is the standard deviation, \( \text{erf}^{-1} \) is the inverse of the error function, and \( \mu \) is the mean of the distribution, with \( B \) set to 0.95. The more stringent performance monitoring and alerting requirement on RNP accuracy can be calculated with,

\[
X = \frac{\sigma \sqrt{2 \text{erf}^{-1}(B)} + |\mu|}{2}
\]

with \( B = 0.99999 \), which is always greater than the accuracy value from the 95% requirement.

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