Designing a 3D Cadastral System Demonstrator: A Case Study

Matthew SMART and Russell PRIEBBENOW, Australia

Key words: Base Parcel, Cadastral Survey, Positions Dataset, Digital Twin.

SUMMARY

In the past decade, the nature and use of the cadastral system has changed significantly. Increasingly, land tenures are being created with explicit limits in the third (height) dimension. At the same time, 3D modelling is expanding in its application in the built environment—from the project level, Building Information Models (BIM)/Digital Engineering; the precinct and city level (Smart Cities); and 3D Geographic Information Systems (GIS) including photorealistic 3D mesh models of natural and built environments. The cadastral system delineates the extent of land interests and as this system relates to the real world, it is inherently 3D. Yet our cadastral systems are constrained by processes that were designed for 2D parcels and paper records, the technology of the time. The cadastral system needs to be transformed to become a digital twin of the cadastre, so that it accommodates 3D digital cadastral information in all aspects of the cadastral lifecycle and supports the integration of cadastral data with BIM and other GIS data.

Queensland has embarked on a process to build a 3D Cadastre demonstrator as part of a National Collaboration framework incorporating input from Victoria and New South Wales. This case study describes the initial research and design of this 3D Cadastre demonstrator. The primary aim is to interrogate three-dimensional data in the cadastral lifecycle and understand how this data can be used to form a digital 3D Cadastre. It will: i) Investigate the emerging needs for a 3D cadastral system; ii) Determine how 3D cadastral datasets can be visualized alongside BIM and 3D GIS data; and iii) Define the digital data components of a 3D cadastral system. This case study positions the base parcel and its survey observations and measurements, which are inherently 3D, as the core infrastructure upon which a 3D Cadastre should be constructed, rather than attempting to add another dimension to existing digital 2D cadastral representations. These base parcels, with their observations and measurements, define the accurate positioning infrastructure for volumetric and building format parcels.

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1. INTRODUCTION

In the past decade, the nature and use of the cadastral system has changed significantly. Increasingly, land tenures are being created with explicit limits in the third (height) dimension. At the same time, 3D modelling is growing in its application in the built environment—from the project level, Building Information Models (BIM)/Digital Engineering to the precinct and city level (Smart Cities) and 3D Geographic Information Systems (GIS) including 3D mesh models for natural and built environments. The cadastral system delineates the extent of land interests and as this system relates to the real world, it is inherently 3D. Yet our cadastral systems remains constrained by processes that have been designed for 2D representation of parcels and paper records.

1.1 Terminology and definitions

This paper refers to two distinct 3D parcel types, that is, parcels that are limited in three dimensions. The first of these are parcels are defined by physical features such as apartments or units, and are referred to as *building format parcels*. The second type of 3D parcel, while not defined by physical features, often define three dimensional spaces in which physical objects are located such as tunnels and bridges. These parcel are referred to as *volumetric parcels*.

In this paper we have refrained from referring to base or primary parcels as 2D parcels because, from a legal definition perspective, their vertical extent is unlimited i.e. in Latin, *cuius est solum, eius est usque ad coelum et ad inferos*, or in English: “whoever’s is the soil, it is theirs all the way to Heaven and all the way to Hell.” This paper will refer to these as **base parcels**. It is important to highlight the difference between base parcels, which constitute the base layer of the cadastre, and primary tenure. Primary tenure is the bundle of rights allocated by the state over land (e.g. Freehold, State Land, Road, Water etc.) whether the land is in its original form or has been reconfigured to include base parcels and possibly also volumetric and building format parcels. Therefore the base or primary layer of the digital cadastre is a subset of primary tenure that excludes both volumetric and building format parcels and provides a seamless topological coverage for the state.

1.2 National collaboration

Many of the Australian jurisdictions responsible for maintaining cadastral, geodeti

c, and addressing systems are undertaking similar and expensive modernisation activities. For example, a recent study by KPMG (2018) found that the modernisation of the environment that supports Queensland’s land parcel and property, geocoded addresses, admin boundaries and positioning infrastructure would cost AU$159M and take up to 7 years to complete when implemented in isolation.

In May 2018, a national collaboration workshop attended by representatives of state jurisdictions and federal authorities identified several emerging opportunities to prove the benefits of national collaboration. Two of these were a Numeric Cadastre prototype and a 3D Cadastre Demonstrator, the latter being led by the Queensland Department of Natural Resources, Mines and Energy (DNRME), and this case study reports on the initial findings of this activity.

1.3 Aims and Objectives for the 3D Cadastre Demonstrator

The aim of this activity is to interrogate three dimensional data in the cadastral lifecycle and cadastral systems and understand how this data can be used to form a digital 3D Cadastre.
In order to achieve this aim we will:

i. Investigate the emerging needs for a 3D cadastral system
ii. Determine how 3D cadastral datasets can be visualised alongside BIM and other 3D GIS data; and
iii. Define the potential digital data components of a 3D cadastral system.

2. EMERGING NEEDS FOR A 3D CADASTRAL SYSTEM

In this section we describe several emerging needs for 3D cadastral data to more accurately represent the legal cadastre, that is, to become a Digital Twin of the cadastre. To achieve this, the entire cadastral lifecycle must remain intrinsically three dimensional, rather than supporting representations of the digital cadastre that contain three dimensional data.

2.1 The 2D Digital Cadastre is an unsuitable starting point for a 3D Cadastre

To date, no implementation of a digital cadastre in Australia defines the legal cadastre, and each jurisdiction's implementation of a digital cadastre has addressed cadastral requirements differently. Queensland's digital cadastre is considered to be a topologically accurate graphical representation of the legal cadastre with relatively accurate dimensions, and this allows us to identify a parcel and those parcels that it abuts. Victoria's current digital cadastre is less topologically accurate because of their support for Application Plans that allow the boundary of a single parcel to be changed without modifying the boundaries of adjoining parcels, which often produces slivers or overlaps. In New South Wales, the majority of the digital cadastre is maintained at the local government level, which is problematic for coordinating and maintaining a state-wide digital cadastre.

Our current cadastral system is constrained by legislation, standards and policies designed for static paper records, and this has resulted in a cadastral lifecycle where height or elevation data is lost. For example, although cadastral surveys capture 3D data for some parcels, this must be abstracted to a static 2D paper or digital representation before it can be registered. Often these representations are also not-to-scale, and do not present the surveyed dimensions e.g. building format parcels. The cadastral boundary data from these static representations are then abstracted again using various map projections to form a map or cartographic 2D representation of the cadastre. This series of abstractions make the 2D digital cadastre an invalid starting point to form a 3D cadastre.

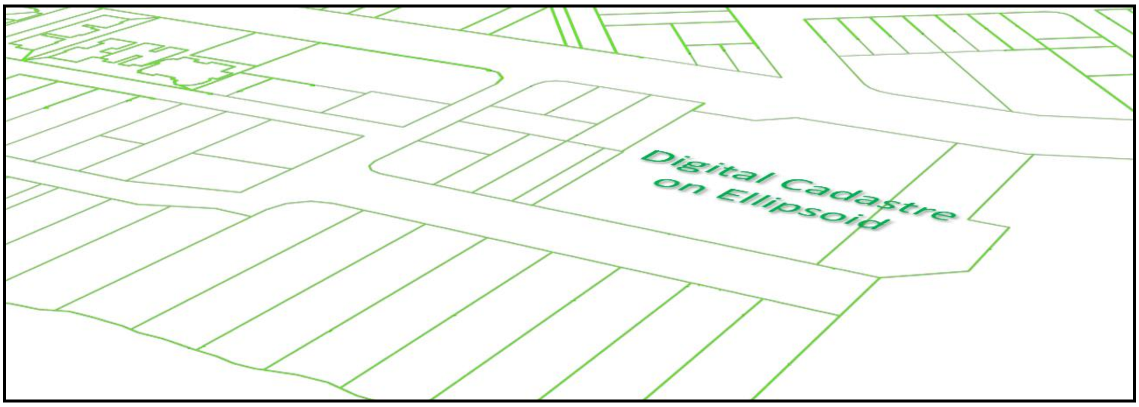

Figure 1. The 2D Digital Cadastre located on the ellipsoid

2.2 A Geodetic and Cadastral Digital Twin

The future-state of a modernized geodetic and cadastral system must evolve to become more than just three dimensional. As the boundaries between BIM, Smart Cities, and GIS break down, particularly as more organisations share the concept of a Common Data Environment (CDE), they will collaborate to create and maintain the complex datasets that will constitute this future digital cadastre as a digital twin of the physical/analogue cadastre.

The digital twin is a digital replica of a real world object or system that incorporates sensors, processes, and actuators that allow it to continuously learn and update both itself and its analogue twin, so it reflects the real world object in its current operational state. This object could be a building or factory, a jet engine, or a mining vehicle; or it can be an entire operational railway that would show the current position of railway vehicles in near real time.

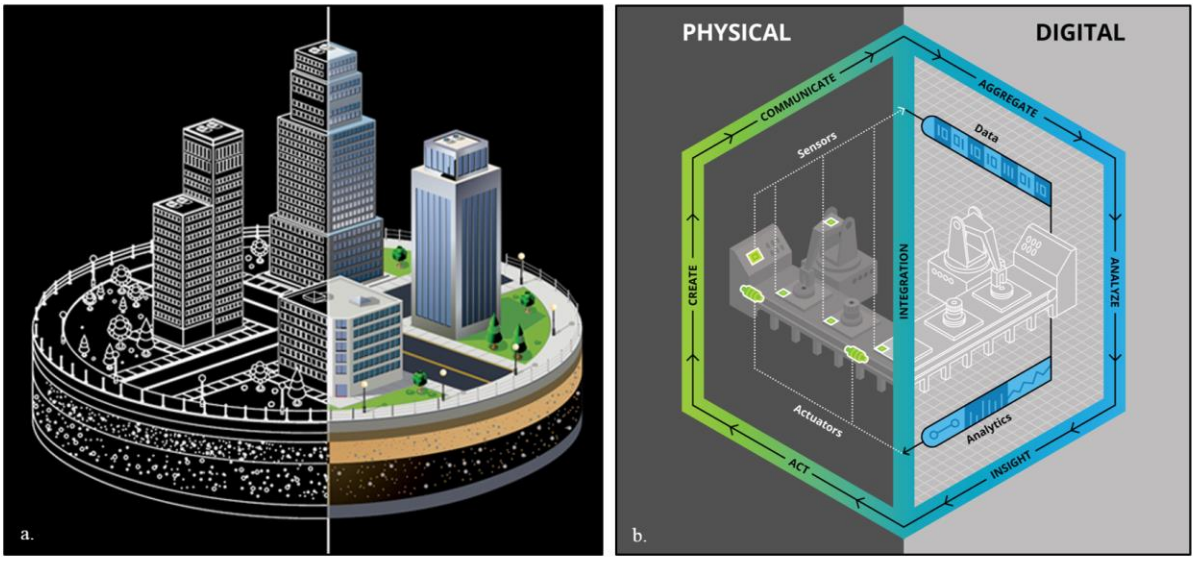

Figure 2. The Digital Twin (source: 2a Gutierrez 2017, 2b Deloitte University Press 2017)

The real world has physical or analogue objects (buildings, tunnels etc.) but also geodetic and cadastral objects e.g. location framework, monuments, land tenure, land titles, and so the new digital cadastre can be the digital twin of these analogue cadastral and geodetic objects. The digital model should also include both data and analytics that provide insight and inform and direct actions for actuators to perform.

CORS and other GNSS devices are obvious implementations of real-time sensors in this geodetic and cadastral digital twin, but this could also include cadastral surveyors and surveying equipment as both sensors and actuators e.g. deploying physical objects such as permanent survey marks or reference marks.

2.3 An evolving 3D cadastral system

In some cadastral systems, such as those used in Australia, paper plans can now include textual statements and perspective or isometric depictions of three dimensional volumes that have helped our comprehension of these spaces. The representation of volumetric and building format parcels has been addressed in previous research (Gulliver et al 2016, van Oosterom (Editor) 2018), and these objects can already be represented in three dimensions in BIM or GIS, however, the 3D representation of base parcels, whether or not they overlap volumetric or building format parcels, has received minimal attention. Cadastral survey observations and measurements can be stored in 3D, particularly when recorded using the modern electronic survey equipment that gained widespread use in the later decades of the twentieth century. The cadastral system needs to be transformed to accommodate and maintain 3D digital cadastral information in all aspects of the cadastral lifecycle, and to support its visualization alongside BIM and 3D GIS data. A complete implementation of a 3D Cadastre must incorporate base parcels, as they provide the accurate positioning infrastructure for volumetric and building format parcels. It should also be possible to include some secondary interests such as easements.

Most 2D digital cadastre datasets are represented on the ellipsoid, where it is possible to conduct mathematically-based spatial analysis, but the research question this paper addresses is: how can we demonstrate what a 3D cadastral system could be? A 3D digital cadastre provides valuable information across the complete property development pipeline, and so has multiple use case such as: identification and interpretation of existing tenure and rights, restrictions, and responsibilities (RRR); city planning; and to determine potentially effected base parcels from proposed underground developments.

2.4 The evolution of spatial data visualisations

The functional and visual capabilities of GIS and the representations of spatial data continue to evolve. Early implementations of GIS provided a 2D cartographic view of spatial data, mostly in the absence of rectified aerial imagery (see figure 3a), and this is the environment that the first digital 2D cadastres in Australia were was designed for. When good quality rectified imagery became available it highlighted potential accuracy issues with the digital 2D cadastre but the representation of the two products was still quite similar (see figure 3b). Later still, GIS started to provide some 3D representations and incorporated Digital Surface Models (DSM), and often aerial imagery was draped over the DSM to form a pseudo 3D representation, though these provided limited functional advancements (see figure 3c).

Figure 3. Spatial data visualisations

Aerial photogrammetry products and technology are evolving at a rapid rate and the integration capabilities and components of a 3D Cadastre must evolve with a similarly rapid pace. The most recent products to be released are centred on 3D mesh models, see Figure 4. These models, in static presentations such as this paper, appear to be photos but are actually an innovative 3D aerial modelling service, based on aerial photogrammetry techniques for the production of location-accurate, high-resolution and fully textured 3D models of the natural and urban environment. On the left-hand-side of Figure 4, the 3D mesh is displayed over the imagery to show its triangulated surface mesh.

Figure 4. AEROmetrex aero3Dpro mesh models, Palace of Fine Arts, San Francisco

3. DATA COMPONENTS FOR A 3D CADASTRAL SYSTEM

There has been considerable work in defining the data model for volumetric and building format parcels in a 3D cadastre (Thompson et al 2016, Aien et al 2015, Ying et al 2012). The majority of this research has related to the visualization and interpretation of these parcels, but an effective and accurate 3D cadastre encompasses more than just parcels specifically defined or limited in three dimensions. It must include the survey observations, measurements of base parcels as well as the cadastral corners of these base parcels that are essential to accurately position volumetric and building format parcels (see section 3.2).

3.1 Three dimensional survey observations and measurements

As asserted in the introduction to this case study, the current cadastral system is inherently 3D, and this is the foundation for our decision to base our 3D cadastre demonstrator on cadastral survey observations and measurements. This presents a number of data issues for cadastral systems that have operated for over a century using processes designed for static paper records. In a cadastral survey, each distance is meant to be the horizontal mean terrain distance between the end points of the line, which could be monuments such as permanent survey marks (PSM), reference marks e.g. Original Iron Pin (OIP), or cadastral corners. While in a 2D digital cadastre these positions are considered point features i.e. with X and Y (or latitude and Longitude) values, in a 3D cadastre they are lines extending perpendicular to the ellipsoid up to the stations at the surface and beyond.

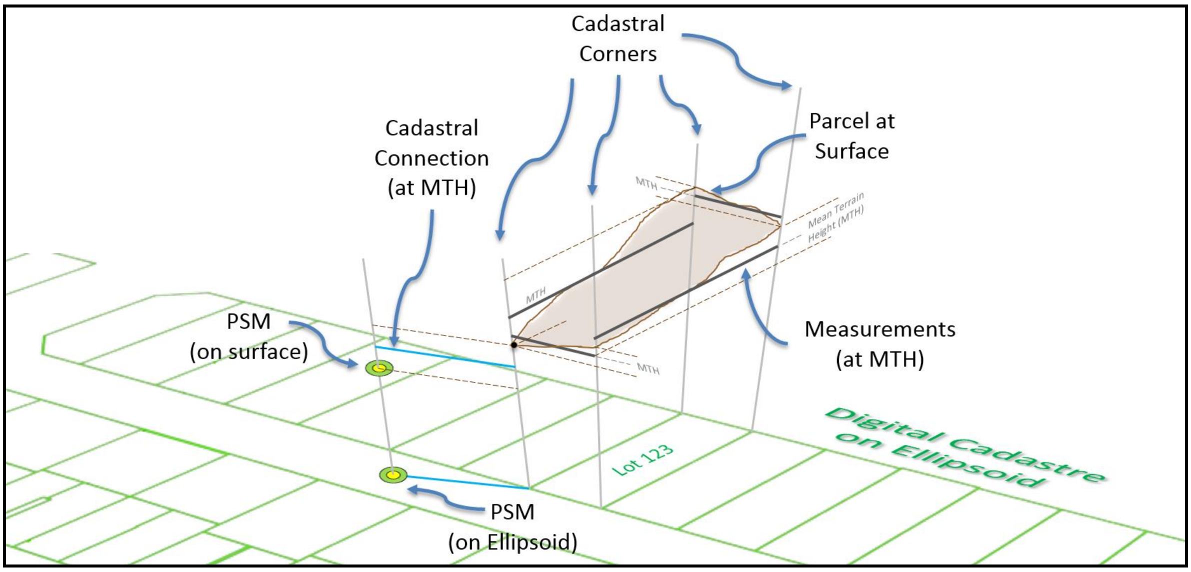

Figure 5. Survey measurements and observations

The black and cyan coloured lines in this diagram depict survey measurements at mean terrain height for the line. It is important to note that, as can be seen, the end points of these boundary lines will not be coincident, unless the parcel is a surface parallel to the ellipsoid. However, with the planimetric view used on traditional cadastral survey plans and in a 2D digital cadastre, the boundary lines are assumed to touch at their end points. Note that in most cases there would be multiple survey observations and measurements over time, and therefore multiple observed positions for each of these cadastral corners, and multiple measurements between these points. However, for simplification purposes, let us assume we have determined the best positions for these cadastral corners and assigned each an appropriate uncertainty.

The logical conclusion of this is that for each cadastral corner we have a vertical line that defines its position, but have not, however, defined the three dimensional location where this cadastral corner (line) intersects the surface. These observations and measurements form a solid core dataset upon which an accurate and effective 3D cadastre can be formed. However, the 3D components of the original survey data are lost from the cadastral lifecycle when producing static cadastral survey plans. To address this we will adopt a similar method to that used in numeric cadastre methodologies, where a Digital Surface Model (DSM) is used to assign heights to survey observations sourced from historic 2D cadastral survey plans.

3.2 Positioning volumetric and building format parcels in three dimensions

Although both volumetric and building format parcels can be defined in three dimensions, the coordinates that position their origin point in three dimensions must be relative to a cadastral corner in a base parcel or nearby reference mark (Gulliver, 2016, p. 479). In Australia volumetric parcels are either defined using isometric drawings with defined Reduced Levels shown against individual stations (figure 6a), or using point tables (figure 6b).

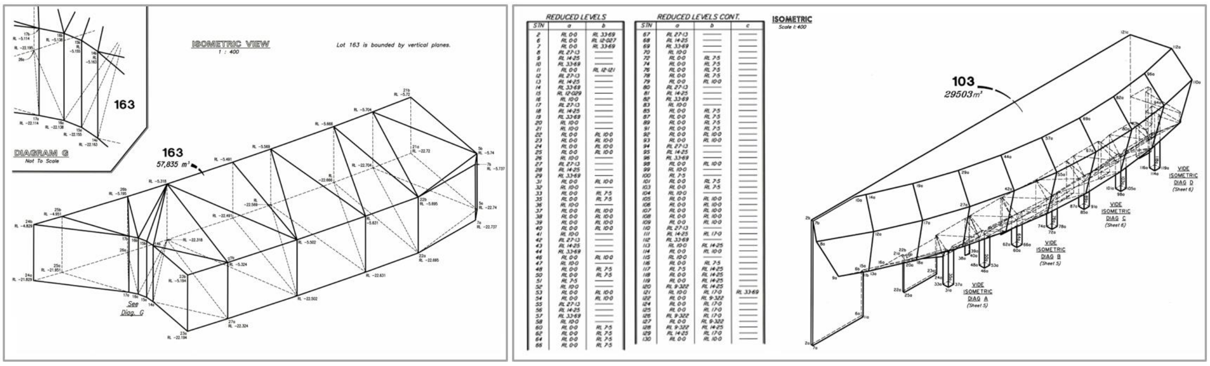

Figure 6. Methods used to define heights for volumetric parcels

Figure 7a describes a simplistic volumetric parcel (Lot 142) that is excluded from the base parcel (Lot 42). The horizontal extent of Lot 142 is defined by corner traverses from station 2 to station 7, and station 5 to station 6. These corner traverses can be used to determine the coordinates for cadastral corners 6 and 7. The Reduced Level table provides the RL for each of the stations that define the spatial object representing the volumetric parcel. Figure 7b provides an isometric view of the volumetric parcel, the 2D base parcel, and a 2D representation of the boundaries of the volumetric parcel. It is important to note that it does not represent the base parcel in three dimensions, only the 2D positions of cadastral corners on the ellipsoid.

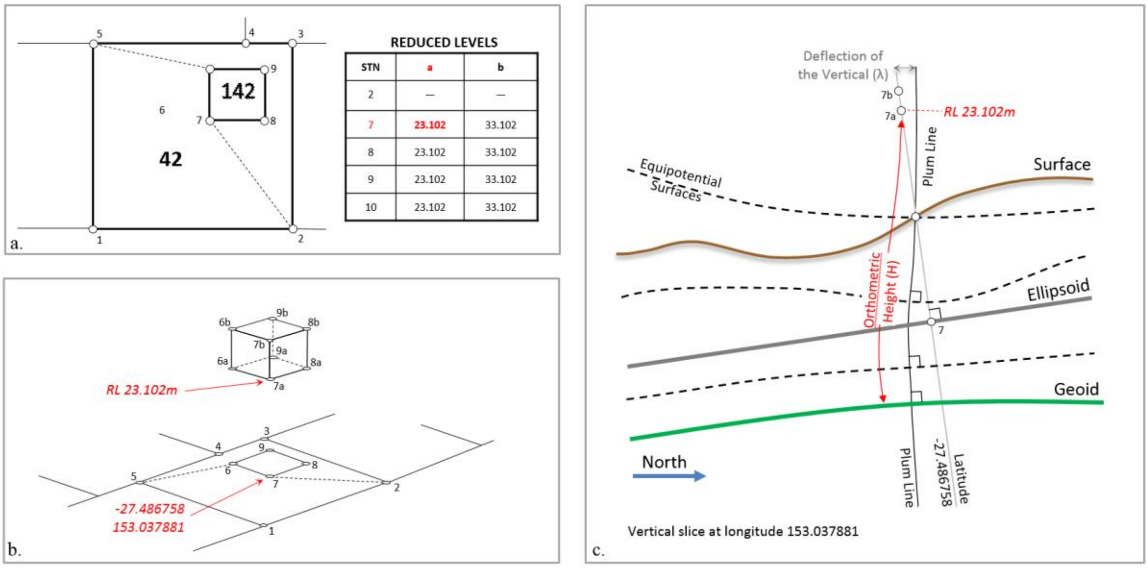

Figure 7. Linking three dimensional parcels to the Base parcel

3.3 Cadastral data components

Building and maintaining a 3D observation and measurement-based Positions Dataset requires only small modifications to the positions dataset definitions of most numeric cadastre methodologies. In the latter half of 2018 the Australian jurisdictions of Queensland and Victoria embarked on a joint co-creation and collaboration exercise to develop a prototype numeric cadastre adjustment methodology, which includes a Positions Dataset. It is proposed to make minor modification to this environment to enhance this position data to include heights for the required observations and measurements. Relative to a 3D cadastre, this Positions Dataset will include:

- **Observed Positions** (for cadastral corners, reference marks etc.) recorded as latitude/longitude pairs: i.e. PID (Unique Position ID), LATITUDE, LONGITUDE. Note that this data can be used to produce *vertical* lines in 3D visualization tools
- **Defined Positions** for two or more stations from cadastral survey plans that define the origin position for volumetric or building format plans, recorded as: PID, LATITUDE, LONGITUDE, HEIGHT. Note that at present in Australia building format plans do not include height measurements
- **Measurements** that define cadastral boundaries i.e. links between reference marks and cadastral corners, or corner traverses etc. recorded as 3D lines defined either by latitude, longitude pairs and height values, or by the unique ID of the Positions they connect: i.e. FROM_PID, TO_PID, HEIGHT. Note that these lines may not have to be stored as spatial objects and that they are all assumed to be horizontal lines relative to the ellipsoid
- **Vertical Faces** that define boundaries in three dimensions. The heights and depths of these faces should be based relative to physical features or volumetric or building format parcels in their proximity.

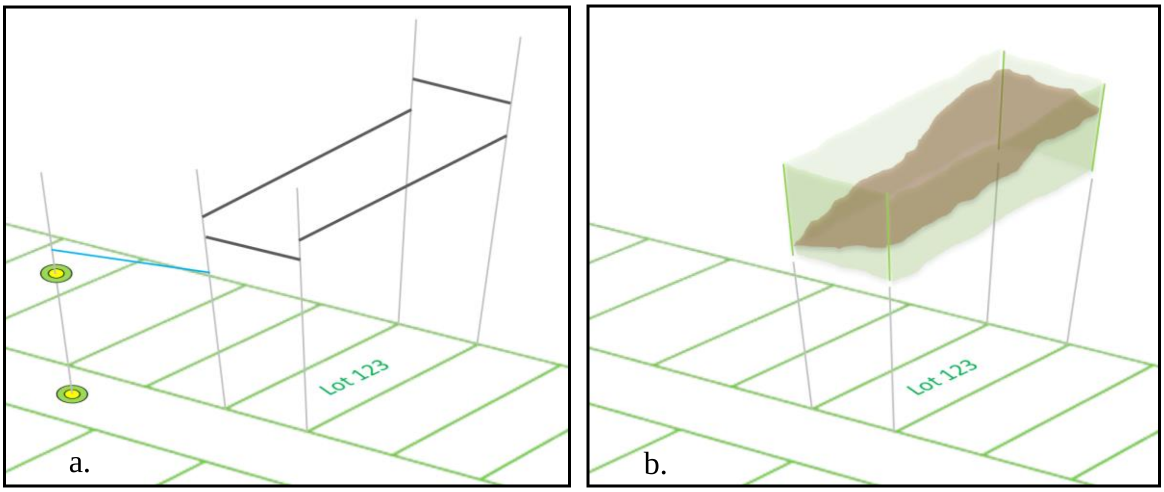

Figure 8. The components of a 3D cadaster

4. REPRESENTING THE DIGITAL CADASTRE IN THREE DIMENSIONS

In this case study, several alternatives were investigated to enable the digital cadastre to be represented in three dimensions, including:

- Projecting base cadastral boundaries onto a Digital Surface Model
- Extruding base cadastral parcels to form volumes
- Extruding base cadastral boundaries to form vertical faces

The following sub-sections describe these attempts, as well as their results and issues encountered.

4.1 Projecting base cadastral boundaries onto a Digital Surface Model

Many attempts at producing a 3D Digital Cadastre or representing cadastral boundaries in 3D visualisation tools have begun with 2D Digital Cadastral data for base land parcels. In a 2D digital cadastre, land parcels are stored as either boundary lines or entire polygons with vertices at cadastral corners and at indicative points along ambulatory boundaries. These parcels are often projected from the ellipsoid onto a Digital Surface Models (DSM) for display alongside terrain or building models.

However, if only the cadastral corners are projected onto a surface model, the boundary lines between these cadastral corners will remain straight lines and will often pass beneath the surface. Figure 9a shows a plan view, and 9b a perspective view of this situation. In the past, this issue has been marginally addressed by breaking boundary lines at predetermined distances and projecting them onto a DSM. But the issue cannot be completely resolved, and this activity significantly increases the number of points required to represent the parcel. Based on our investigation, this option for the display of base parcels was ruled out for use in the 3D cadastre demonstrator.

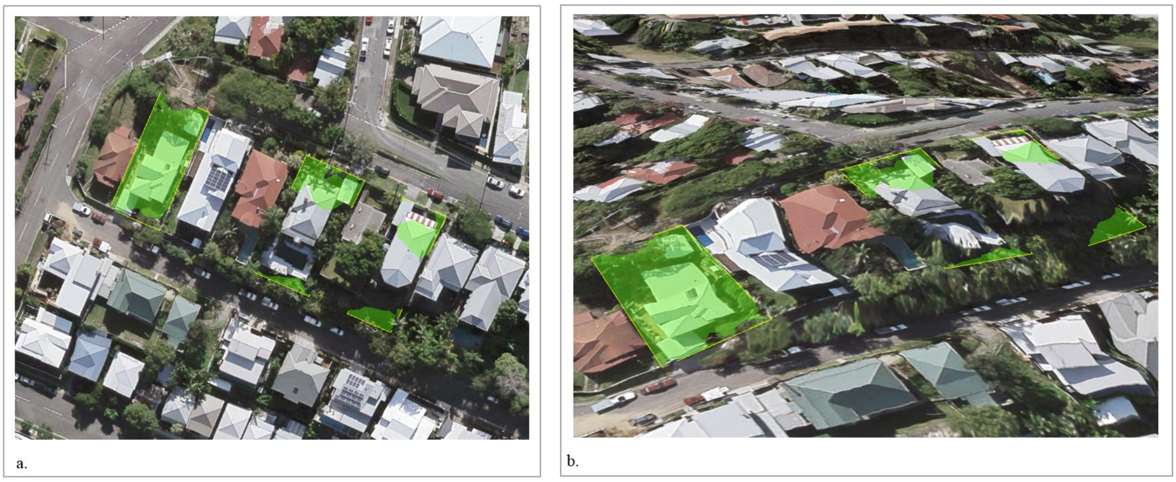

Figure 9. 2D cadastral parcels displaying underneath the Digital Surface Model

In modern GIS, the issue described in section 4.1 has be alleviated by projecting linear features onto the DSM as raster objects, see Figure 10. However, this does not address their use in BIM and other engineering visualization and analysis tools or their display alongside 3D mesh products.

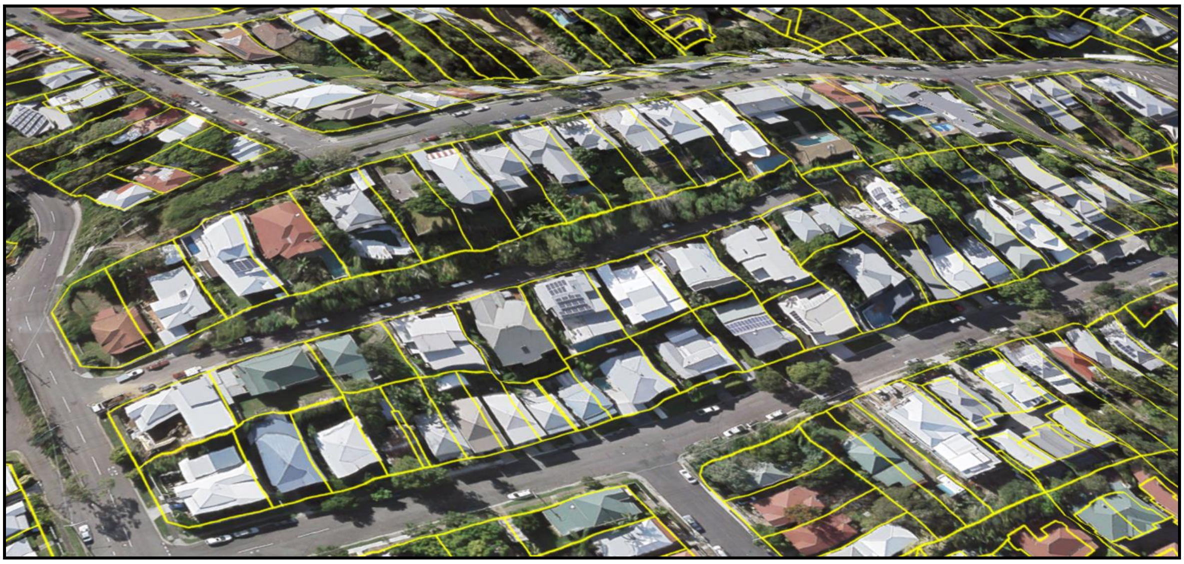

Figure 10. Projecting digital 2D cadastral boundaries onto a Digital Surface Model

This method of displaying parcel boundaries over traditional aerial imagery has been used for many years and can continue in this limited capacity, but it is impractical alongside emerging 3D products such as city or building models and imagery products such as the aero3Dpro mesh models shown in Figure 4. Again, this option for the display of base parcels was ruled out for use in the 3D cadastre demonstrator.

4.2 Extruding base cadastral parcels to form volumes

This method has been demonstrated by many researchers, for example see Figure 11 (Ying et al, 2012). Ying's representation provides a reasonable indication of the space under the control of the base parcel's owner(s), but does not address how the vertical limits of these parcel volumes are defined. As a visual representation this method is flawed because it depicts a specific upper surface that implies the existence of an upper limit, which is not legally there.

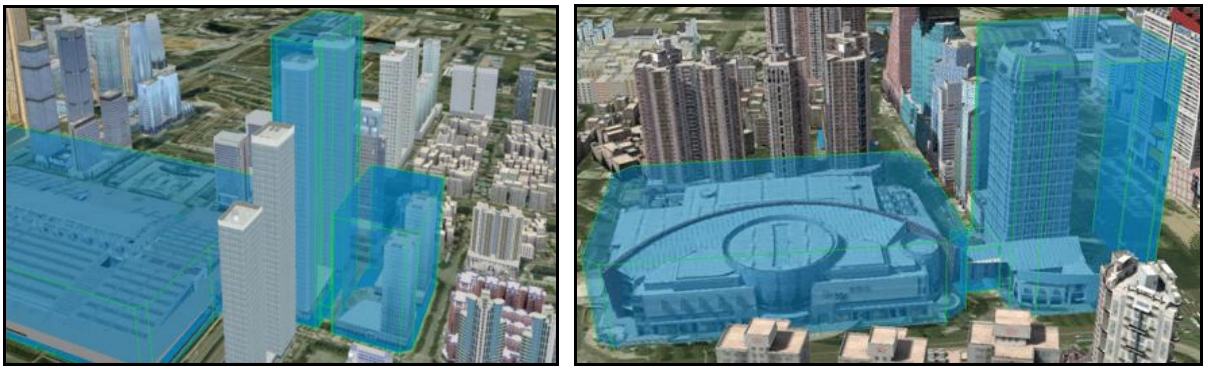

Figure 11. Extruding 2D cadastral parcels to form volumes (Ying et al, 2012)

Our initial 3D cadastre investigation considered the option of using LiDAR to determine the physical location of buildings etc. that could be used to define upper vertical limits of the space controlled by base parcels, but this data is not currently available over entire jurisdictions or captured at sufficiently regular intervals to update the vertical limits in response to construction, demolition activities, or natural events.

Victoria are currently formulating a research proposal to use LiDAR and photorealistic mesh models to estimate floor levels and building heights for building format parcels. However, this option for display of base parcel extents has some merit in large cities but its practical application outside city centres is problematic and unrealistic for rural areas, particularly in outback areas of Australia that have never been surveyed.

4.3 Extruding base cadastral boundaries to form vertical faces

Interests in land have traditionally been issued over an area with boundaries that are defined in the horizontal plane, and the vertical extent is unlimited from a legal definition perspective. Representing this visually both above and below the surface is impractical. See Figure 12a, where the property boundaries of base parcel are all extended well above the natural surface. Here this data obscures almost all useful information, reversing the well-known idiom so that *we cannot see the trees for the forest*. For spatial analysis it is possible to use this information, but it remains impractical to view it alongside city models and other 3D GIS data.

The proposed solution to this is to limit the visualisation of these vertical faces to practical heights, and so mimic the traditional means that has been used to delineate property boundaries for melena i.e. fences or walls. This is demonstrated in Figure 12b, where property boundaries are extruded to a uniform height of 20m.

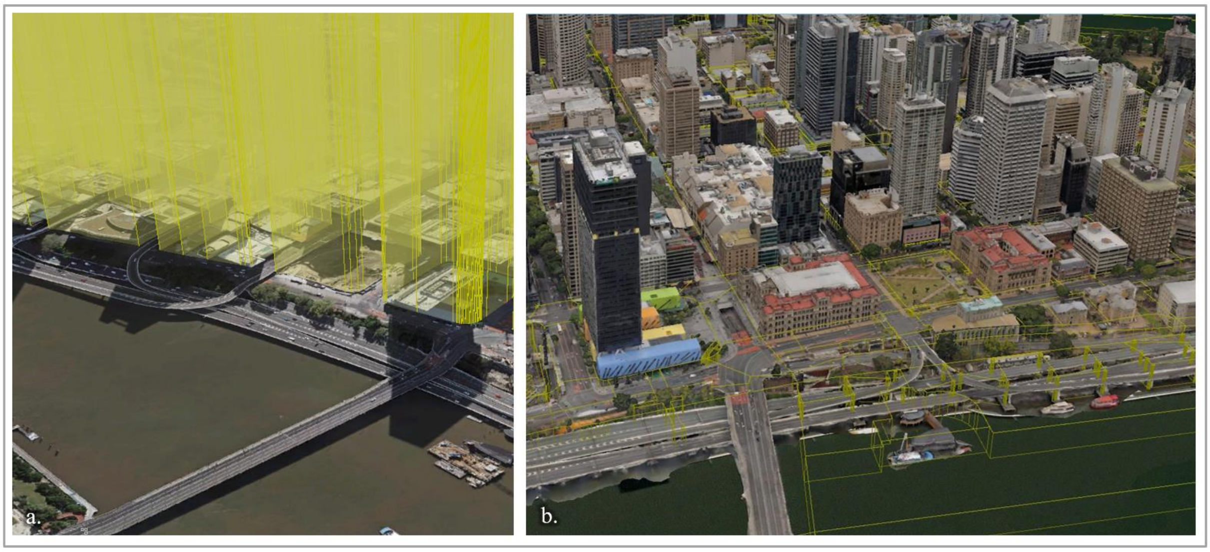

Figure 12. Extruding 2D cadastral parcels to form vertical faces

5. CONCLUSION

The cadastral system delineates the extent of land interests and as this system relates to the real world, it is inherently 3D. The 3D cadastre is not cadastral boundaries visualized in BIM or GIS, nor it is a pretty picture; it is the underlying principle that our future cadastral systems must maintain the veracity of this 3D data of its measurements, observations, and representations throughout the cadastral lifecycle. This must inform the next phase of activities of the 3D cadastre demonstrator, where we will elaborate on our vision for this 3D cadastre, not to show what the 3D cadastre is, but how 3d cadastral data can be maintained and how it could be represented alongside BIM and other GIS data.

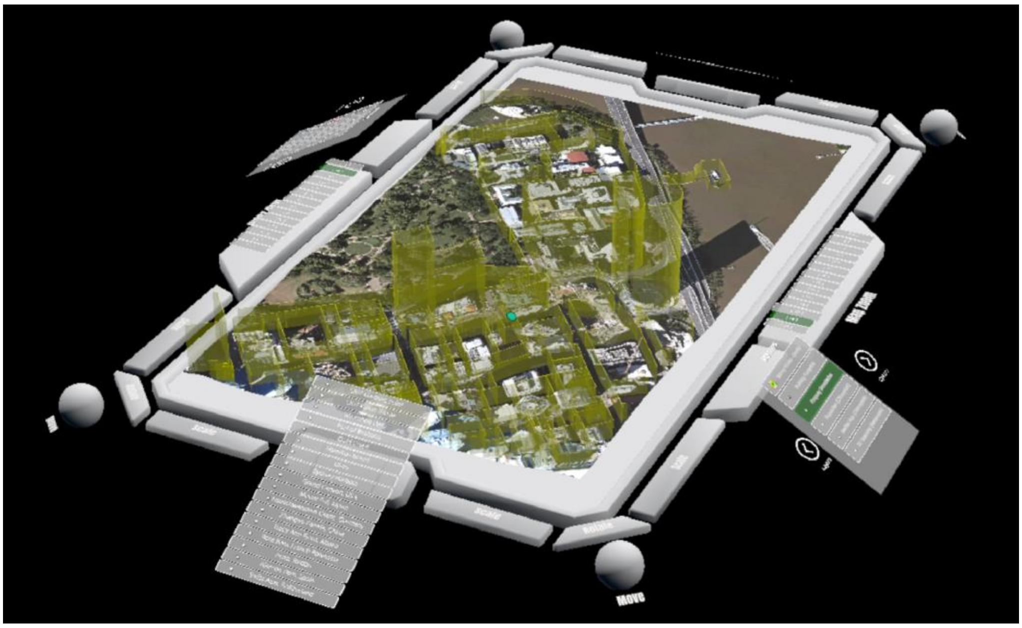

Figure 13. Augmented reality map table for the HoloLens (James 2018)

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BIOGRAPHICAL NOTES

Matthew Smart is an independent spatial consultant with over 30 years in the spatial industry working with cadastral, property and asset data across many industries in both private and public organisations. He was a founding member of the Australian Spatial Science Institute (SSI) and former committee member of the Queensland chapter of AURISA, and is currently completing a Research Master's Degree through the School of Communication at the Queensland University of Technology.

Russell Priebbenow is the Director of Cadastral and Geodetic Services in the Department of Natural Resources, Mines, and Energy. He is a registered cadastral surveyor with over 35 years of public sector experience in surveying and mapping, including more than 25 years involvement with legislation and policy. Prior to this, he attained a PhD from the University of Queensland for research into the mapping applications of imagery from the SPOT satellite. He is a member of the Surveyors Board of Queensland and also the Queensland member of the Australian and New Zealand Intergovernmental Committee on Surveying and Mapping. He is a Fellow of the Surveying and Spatial Sciences Institute.

CONTACTS

Matthew Smart
Technical Lead, QLD Cadastre Transformation Project
Queensland Department of Natural Resources, Mines, and Energy
GPO Box 2454
Brisbane QLD 4001
Australia
Phone: +61 (0)439 774 198
E-mail: Matthew.Smart@daf.qld.gov.au
Website: www.dnrme.qld.gov.au

Russell Priebbenow
Director of Surveys, Land and Spatial Information Group
Queensland Department of Natural Resources, Mines, and Energy
GPO Box 2454
Brisbane QLD 4001
Australia
Phone: +61 (0)439 774 198
E-mail: Russell.Priebbenow@dnrme.qld.gov.au
Website: www.dnrme.qld.gov.au