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DOI
10.4233/uuid:5753e199-0478-45e3-a822-8d1cd64d40cc

Publication date
2019

Document Version
Final published version

Published in
Proceedings of the 8th Land Administration Domain Model Workshop (LADM 2019)

Citation (APA)
Thompson, R., & Oosterom, P. V. (2019). A Suggested Terminology for Point-Like Entities in a Bi-Temporal Representation of 2D and 3D Land Administration Data. In P. V. Oosterom, C. Lemmen, & A. A. Rahman (Eds.), *Proceedings of the 8th Land Administration Domain Model Workshop (LADM 2019)* (pp. 51-72). International Federation of Surveyors (FIG). https://doi.org/10.4233/uuid:5753e199-0478-45e3-a822-8d1cd64d40cc

A Suggested Terminology for Point-Like Entities in a Bi-Temporal Representation of 2D and 3D Land Administration Data

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Key words: Cadastre, 3D Cadastre, 3D Geoinformation, Land Administration, Temporal, Bi_Temporal.

SUMMARY

The prime purpose of Cadastral data – whether in the form of maps, survey plans or notes, or a digital database is the definitive demarcation of the extent of properties – and can be seen primarily as a decision support facility ("Can a structure be built here?", "Where can I build a fence?", "Should I buy this property"?). There are, however many additional uses for which this information has been applied – such as a base for the recording of assets such as light poles, underground cables, etc. and as a history of the pattern of land use and subdivision. Although secondary, these uses are important, and should be adequately supported.

It is a fact that the determination of cadastral boundaries can only be carried out to a certain accuracy, and that that accuracy has been improving over time. Older surveys had been carried out with limited control, and using equipment with a low intrinsic accuracy by modern standards. As a result, later surveys provide an opportunity to improve the positioning of existing boundaries. In addition, engineering works such as road building, can provide a source of high accuracy position data that can be applied to low accuracy data.

This argues that the accuracy of boundaries should be improved in the historic record of the cadastre – after all we would like to see our historic parcels in the position we now know them to have been – so that they are comparable with current boundaries. Likewise, we need to correct inaccuracies in the attributes of the spatial objects and the topology between them (e.g. which spatial units are adjacent to a given object).

On the other hand, we must not lose sight of the decision-making side of the requirements – so that a past decision can be reviewed in relation to the data as it existed then. If the current knowledge in the database of today is used to review old decisions, they may seem irrational. Data custodians are well aware of this issue, using terms like "update" to indicate a "real-world" change, while using "upgrade" to indicate an improvement of the database representation not accompanied with a change "on the ground"; however the database software has not carried this knowledge through – resulting in its loss.

This argues for a database with bi-temporal history – where our current best knowledge of the history of the cadastre is recorded (and that history is corrected and maintained), while our past knowledge of the data also recorded as an audit trail (so that we can ask questions like "what did we in 2017 think the definition of this property was in 1994?").

The different historic records, combined with changes of datum, can lead to confusion in terminology – where words such as “point”, “position”, “boundary” become rather overloaded. This paper is intended to provoke discussion of terminology to clear up this confusion, and potentially to assist with an extension of the temporal model in the LADM to accommodate bi-temporality.

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1. BACKGROUND

Cadastral data has some characteristics that are different from more conventional Geographic Information. The mixture of 2D and 3D real estate objects are the most obvious, but also the nature of the boundaries of objects is significant. “It has been pointed out repeatedly that only few objects in geographic space have natural boundaries which are sharp and well determined (Couclelis 1992). Most geographic objects seem to be an abstraction of things which have unclear, fuzzy boundaries, if they have boundaries at all. The list includes most natural phenomena, from biotope to mountain range; extensive research efforts center around soil type data (Burrough 1986) and often use the techniques of fuzzy logic (Zadeh 1974). Nevertheless, many practically used GIS model reality in terms of crisply delimited objects. Cadastral systems, GIS used for facilities’ management and automated mapping (AM/FM) and communal information systems all are appropriately oriented towards distinct objects with well defined boundaries. The same systems, with the same models are also used to manage soil maps and land use data, where the fiction of sharp boundaries contrasts with our view of reality” (Frank 1995).

In real-world terms, cadastral boundaries are primarily sharp ”fiat” objects, but some are less clear ”tangible” objects such as river banks (Smith 1995, Thompson, van Oosterom et al. 2019). In all cases, the database representation is in terms of points, lines, surfaces etc. that are sharply defined. At best these definitions are qualified by accuracy metadata, however the action of changing the coordinate values of a ”point” in the definition of a cadastral peoperty can be a result of at least seven different identified cases (identified in Section 1.2), with different results for current and historic information:

Where changes of attributes and/or topology are involved, they may also be caused by true events, or database correction, however on occasions it is difficult to separate the reasons for individual changes.

Section 1 introduces the topic, presents some issues in the modification of point-like object representations, and re-states some existing definitions. Section 2 suggests some basic terms, presents some issues in database representation, and re-visits the database transactions (update and upgrade) introduced in Section 1. Section 3 considers the concept of bi-temporal history as a technique to solve these issues, and as a concept relating to the LADM in its current form, and the upcoming second edition. The extension of these into three spatial dimensions is addressed in Section 4, with conclusions and suggested future research in Section 5.

1.1 The concept of the Point

It may be a matter of surprise that the definition of a point is quite a complex issue. ISO19107 defines a point as a "0-dimensional geometric primitive, representing a position" (ISO-TC211 2003 Page 10) and introduces the concept of "Direct Position" which defines the coordinates of a point in space. It does not restrict this to 2 or 3 coordinates, so could presumably be in terms of (x, y, z, t)[1]. A Direct Position is related to a Coordinate Reference System (CRS) (directly, via an enclosing geometric object or using default defined for the whole database), This is then used to define the GM_Point class, which is the simplest geometric primitive (GM_Primitive), and the basis of all other primitives. This is an apparently simple approach, but can lead to confusion in the Cadastral database field. Some further discussion is needed.

The Coordinate Reference System (CRS) specifies how the coordinates are to be interpreted. For the purpose of this discussion CRS is effectively equivalent to "Spatial Reference Framework" (SRF) and "Spatial Reference System" (SRS), with the latter term being used here. A series of standard SRS have been defined and given Spatial Reference Identifiers (SRID) to facilitate exchange of spatial data.

1.2 Point Movements

Consider a (3D) point $p = (x, y, z)$ which is modified in the database to a new direct position $p' = (x+\delta x, y+\delta y, z+\delta z)$.
This may be the result of a number of cases:

1. "Tangible Movement": The point may have been physically moved a small distance on the ground (p to p') – for example a survey control point may be moved. This will affect any observations of (say) cadastral corners that are fixed in reference to the mark in the future, but should not affect any historic points referred to it.
2. "Correction": The recorded position p may be found to be wrong, and it is corrected to p'. This change does affect history – the point has always been in the corrected position.
3. "Natural Movement": The point may be a vertex along a natural ambulatory boundary, or the intersection of such a boundary with a surveyed line. The actual definition of the point is given by the natural feature, and it may be moved each time the feature is observed.
4. "Datum Change": There may be a change of SRS throughout the database. The values of the coordinates have changed, but using the new SRID, the same physical location should be determined (p in the old SRID should equate to p' in the new). The database could be completely converted to the new SRS, or a historical tag added to indicate that before the event, all coordinates are in the old SRS.
5. "Dynamic Datum": The coordinates may be referred to a Dynamic Datum (Donnelly, Crook et al. 2015) (see Section 2.1), in which case the coordinates of a point which is

[1] To save excess verbiage, unless otherwise noted, in this paper (x, y, …) is taken to include geographic coordinates – with longitude as x, and latitude as y.

fixed to the ground (such as a cadastral corner) are changing on a daily basis with continental drift.

6. "Local Deformation": There may be a local or semi-local constant and predictable movement of the earth's surface not associated directly with continental drift. Some examples are subsidence or upthrust and soil creep.
7. "Unanticipated Deformation": There may be a local event such as an earthquake, landslide, etc. that requires the re-positioning of many points over a local area. This event is assumed to be unanticipated and unpredictable.

The effect on the history of the Cadastre varies depending on the reason for modification of a direct position coordinates, so to clarify the situation, some terminology is proposed.

1.3 Externally Defined Terms

Spatial Unit: A "Single area (or multiple areas) of land … and/or water, or a single volume (or multiple volumes) of space" (ISO-TC211 2012 Page 6).

Fiat Object: "exist only in virtue of the different sorts of demarcations effected cognitively by human beings" (Smith 1995 Page 477).

Tangible Object: (Smith uses "Bona Fide") "exist independently of all human cognitive acts" .

Transaction Time: "time when a fact is current in a database and may be retrieved" (ISO-TC211 2002 Page 6).

Valid Time: "time when a fact is true in the abstracted reality" (ISO-TC211 2002 Page 6).

Instant: "point representing [a] position in time" (ISO-TC211 2002 Page 4)

Direct Position: "… hold the coordinates for a position within some coordinate reference system." (ISO-TC211 2003)

2. PROPOSED TERMINOLOGY

The scope of this paper is restricted to "point-like" objects – those of zero dimensions.

2.1 Point-Like Objects in 2D

The first part of this discussion considers only points with two spatial dimensions – assuming a surface with no topography (i.e. a plane or the surface of a spheroid), and no 3D spatial units to consider. It is assumed that there exists an International Terrestrial Reference Frame (ITRF), which in effect embeds a set of axes in the Earth, and defines a set of polar coordinates (Latitude, Longitude) that do not change as the continents drift or other deformations occur. In such a reference system, a cadastral spatial unit's coordinates will be constantly and steadily changing. (It should be noted that "ITRF, which is sometimes described as a 'dynamic datum', is in reality a static reference frame with kinematic coordinates for ground-fixed physical features" (Donnelly, Crook et al. 2015 Page 237). Bearing this in mind may save some confusion in the following discussion, but "dynamic datum" is in common parlance, and will be used here).

Constantly changing coordinate values would be inconvenient for day-to-day usage in a Cadastre, so a Local Reference Frame (LRF) is used. This remains fixed relative to local tectonic plate movements (at least to the accuracy we need). It is expected that a set of coordinate transformations exist such that if $p = p_t(x, y, t)$ is the ITRF representation of the 2D location of the point at instant t, and $p=p_l(x', y', t)$ is the same location represented in an LRF at the same instant of time, that functions such as:

$x = x_{lt}(x', y', t), y = y_{lt}(x', y', t)$
$x' = x_{tl}(x, y, t), \quad y' = y_{tl}(x, y, t)$
which can provide a two-way transformation between the two frameworks.

This leads to a suggested set of point-like objects for discussion:

EarthFixedLocation: This is a location which remains the same position relative to the ITRF over time. (No assumption of any object occupying the position or any measurement of the location having been made).

PlateFixedLocation: This retains the same position relative to the local tectonic plate over time. (No assumption of any object occupying the position or any measurement of the location having been made). An example is the location of a Cadastral corner. Viewed in relation to an ITRF, this ceases to be a point and becomes a trajectory. See Figure 1.

PointInstant: a tuple of coordinates, referred to an SRS of a point at an instant of time. Coordinates would be (x, y, z, t).

DirectEarthPosition: By analogy with DirectPosition defined in ISO19107, this is a tuple of coordinates (e.g. lat, lon) referred to an ITRS as mentioned above.

DirectPlatePosition: This is a tuple of coordinates referred to a LRF (based on this tectonic plate).

DirectPlateTrajectory: Where a PlateFixedLocation is referred to an ITRS, this is not a point, but a trajectory of PointInstants (x, y, z, t) indicating the movement of the PlateFixedLocation. See Figure 1.

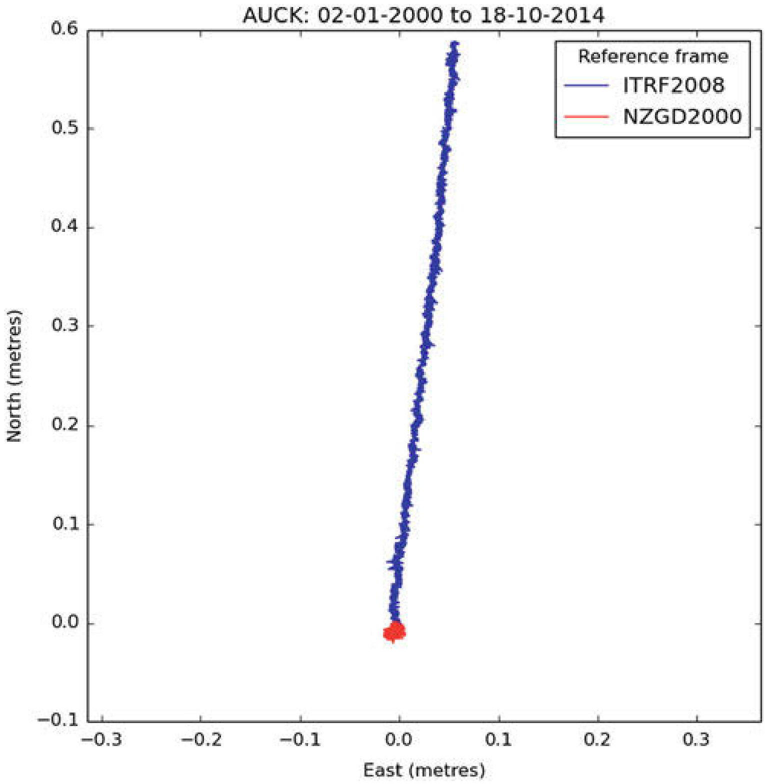

Figure 1 Example of the trajectory of a PlateFixedLocation (a reference point in Auckland New Zealand) over a 15 year period. The position in relation to an ITRF is blue and red in relation to an LRF (NZGD2000). Note that "The trajectory in terms of the local frame is almost static". (Reproduced from Donnelly, Crook et al. 2015 Page 239)

Thus a cadastral corner is an instance of a PlateFixedLocation, located by a DirectPlatePosition (static datum), or a DirectPlateTrajectory (dynamic datum). But this is only true for a period of time. Once modifications to the real-world objects and database representations are permitted, more objects need to be considered:

PlateFixedPoint: A real-world location that is fixed relative to the continental plate. It may be the location of a tangible object – such as a survey mark, or a fiat object such as a node along the boundary of a spatial unit.

EarthFixedPoint: A real-world location that is fixed relative to the Terrestrial Reference Frame. It is unlikely to be the location of a tangible object (unless for an instant only), It might be a fiat object, such as the intersection of the Equator with the International Date Line.

Point: In this paper this term is used as a locator for cadastral corner, survey point, etc – any PlateFixedPoint that is of interest to the cadastre. A point cannot move relative to the plate – if a cadastral corner is moved relative to the Earth's surface, it must be associated with a new Point, creating a new version of the cadastral corner.

2.2 Database Representation of Point-like objects

As described in Section 1.2, a Direct Position (and therefore the coordinates of all points and other geometric primitives) must be related to an SRS (by an SRID). One possible approach is that each representation carries the SRID – so that $p = p(x, y, z, s)$ or $p(x, y, z, t, s)$, where s is the SRID used to interpret the coordinates, and t is the date/time that the coordinates were determined, and is needed if a dynamic datum is involved.

ISO19107 also permits the SRID to be specified via an enclosing geometry, so it could be, for example be recorded on each Spatial Unit, and apply to each point in the definition of the boundary. It could also be specified at the city, state, or country level in an extended database. Commonly, a single specified SRID is defined for the whole database, with all incoming data being converted to that frame. If a non-dynamic SRS is in use, it will be necessary from time to time (typically a few decades apart) to convert to a new SRS. This can be a sweep through the database applying a set of functions, which is not difficult in itself, but may lead to topological errors in some database structures.

However these are not the only possibilities. It may be decided not to back-date a change of SRS to historic geometries applying it to current data only, so that point positions time-stamped before a certain date are in an older SRS, while after this date a new SRS is in use.

2.3 Point Movements Revisited

Returning to the cases identified in Section 1.2:

1. Tangible Movement: The actual object or corner is moved relative to the earth surface. A new Point must be created, and the object or corner linked to the new Point. This means that the history of the object or corner will show a jump in the position at this instant of time. In Figure 2B, the new plate fixed point p' is created, and the cadastral corner moved to it.
2. Correction: The recorded position is corrected. This is effected by a change to the coordinates of the point itself. Any linked objects are "carried along" with the change. The history of any linked objects will show that they were always in the adjusted position, (but see Section 3 on the bi-temporal issues involved). In Figure 2, there is no change to the real-world situation, but the coordinates on p will change.
3. Natural Movement: The point associated with a natural ambulatory boundary. This is treated as in case 1, but with the knowledge that the point location as surveyed does not have enduring legal status. This is a case of a PointInstant, because it is valid only for the instant of its measurement. Any future locations will depend on its being revisited.
4. Datum Change: This has been partially discussed in Section 2.2, but in terms of the real world objects, the Points are adjusted to the new coordinates (and link to the SRS). The objects linked to the points are not affected because their position has not been changed. The Point records will carry history of the change, but the cadastral corners, marks, etc will not.

5. Dynamic Datum: Where coordinates are referred to a Terrestrial Reference Framework. This requires a set of coordinate velocities to be determined for each point. The Point records will probably not change, and the corner, mark etc records will certainly not. In Figure 2D, this is shown relative to an TRF – the points, corner, boundaries, and LRF lines have all moved. This is discussed further in Section 2.4.
6. Local Deformation: Local or semi-local constant and predictable movement of the earth's surface. This is probably seen as a distortion of the LRF, or a variation of the velocity field – see Section 2.4. If it is not recognised as an effect, it will be (spuriously) identified as case 2, or even worse as case 1.
7. Unanticipated Deformation: Such as earthquake. All cases differ in extent and effect, but many new points will have to be created, and cadastral corners re-linked. Careful judgment is needed, and survey marks and such landmarks will have to be reviewed and replaced as needed. It would be unlikely that Point records would be moved – and so there would be no back dating of their positional information. The actual cadastral database objects would be affected, and carry bi-temporal historic record of the event.

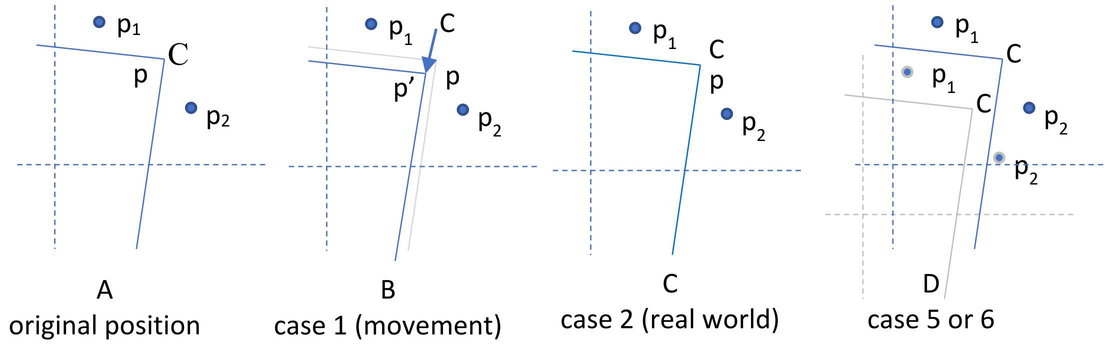

Figure 2 Movements of a cadastral corner under various changes. Points p1 and p2 are assumed to be physical markers near the corner C. The location of C is marked as p. The two dashed lines indicate a local reference frame coordinate values.

2.4 Dynamic Datum

As mentioned in Section 2.1, this is a confusing term, but, being in general use it is adopted here. In effect, all the point-like objects in the cadastre (such as boundary corners, traverse points, survey marks …) are recognised to be PlateFixedPoints, while the coordinate system is based on an ITRF. Thus a Point will be represented by a DirectPlateTrajectory, meaning that the question "What is the Latitude and Longitude of the corner of my property?" cannot be answered except as a rough approximation. The question needs to be qualified by "at date …".

To provide an answer to this question, there are a number of possible solutions. One is that each Point records the velocity of the plate at that location – so that $p = p(x_t, y_t, z_t, v_x, v_y, v_z)$ records the point location at time t. In order to find the coordinates at date t', $x = x_t + v_x(t'-t)$, $y = y_t + v_y(t'-t)$, $z = z_t + v_z(t'-t)$. The values x_t, y_t, z_t and t are obtained from the SRS, which is located using any of the methods discussed in Section 2.2. This method has little to recommend it – the maintenance problems are obvious, as is the effect of a mis-recorded velocity.

At the opposite extreme – a small jurisdiction within a stable continental plate may elect to store just one value for (v_x, v_y, v_z) for the whole cadastre. Note that the Australian plate is very stable, but one of the faster-moving, while New Zealand, being at the edge of a plate, while slower moving is more complex.

Donnelly, Crook et al. (2015) approach this issue in terms of a Plate Motion Model (PMM), which may at its simplest use a rotational/translational transformation. In New Zealand a 14 parameter transformation is in use, but although a single model is expected to be valid for all Australia, a number of submodels is required in New Zealand.

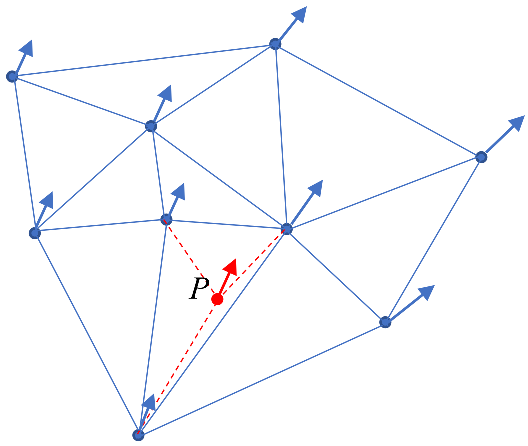

Figure 3 A Vector TIN in 2D. The blue nodes are points at which the velocity (represented by the vector arrows) is known. The velocity at point P is interpolated from the vertices of the enclosing triangle.

A pragmatic solution for the cadastral situation is the vector TIN (Triangulated Irregular Network). In Figure 3 the arrows indicate the measured velocity (v_x, v_y, v_z) of the plate at the particular points. Using the usual techniques of the TIN (Peucker, Fowler et al. 1978), the velocity of the point *P* (in red) is linearly extrapolated from the vertices of its containing triangle. For a large, stable plate like Australia, the triangles will be large geographically, but not numerous. But for New Zealand, a larger number of smaller triangles will be necessary. This does not address the modelling required to generate the TIN, but suggests a technique to make the modelling results available to Cadastre users.
An advantage of this method is that a local but predictable and constant region of distortion to the plate movement (Case 6 in Section 1.2) can be incorporated by a relatively simple vector addition of the distortion to the plate movement TIN. For example, in Figure 4, if the shaded region is a region of local distortion, extra points can be added in the area as shown (with the movement vectors being the sum of the distortion vectors with the plate movement vectors obtained from the original TIN). Thus a single implementation can accommodate plate movement and predicted local deformation.

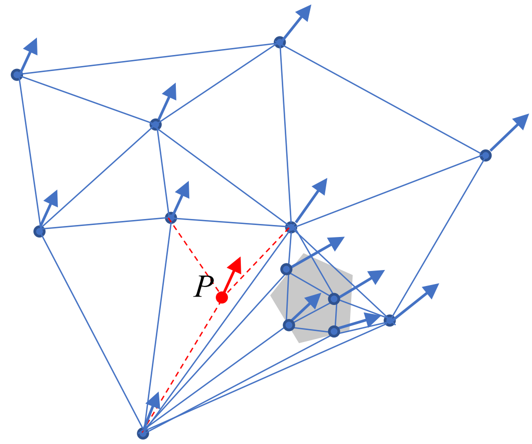

Figure 4 A plate movement TIN, with a local regional distortion (shaded) added.

Other solutions are possible – such as the "distortion grid", which is a 2D rectangular mesh of velocity vectors covering the region. It is probably a faster solution in processing time for requests, but more storage-intensive.

3. BI-TEMPORAL HISTORY

Analogously to the spatial reference frameworks, there exist an international standard temporal framework UTC (Coordinated Universal Time or Zulu Time), and many local frameworks. This is beyond the scope of this paper, which assumes that a suitable framework has been chosen for the database, and a computer system date/time with a fine granularity is available.

In the bi-temporal history model, two forms (or dimensions) of time are involved. One is the real-world time (known as "valid time") and the other is the time a piece of information enters the database (known as "transaction time") (Snodgrass, Böhlen et al. 1998). This can be accommodated by two types of event and three types of relation (Figure 5):

ValidEvent: An event which happens in the real world. The date/time in this object is the actual time the event happened. (Although well accepted, the term "valid" is unfortunate, because not only does it imply some kind of validation operation, the TransactionEvent is no less "valid").

TransactionEvent: The entry or modification of some data in the database. In this case, the date/time is supplied by the computer system.

To include the temporal aspects in a Relational Database, the following three definitions are defined by Jensen, Clifford et al. (1994 Page 54):

ValidTimeRelation: "A [database] relation with exactly one system supported valid time. There are no restrictions on how valid times may be incorporated into the tuples; e.g., the valid-times may be incorporated by including one or more additional valid-time attributes in the relation schema, or by including the valid-times as a component of the values of the application-specific attributes." (That is to say the time stamps may be administered by the database schema or by the application, and may be of granularity appropriate to the application).

TransactionTimeRelation: "A relation with exactly one system supported transaction time. As for valid-time relations, there are no restrictions as to how transaction times may be incorporated into the tuples."

BitemporalRelation: "A relation with exactly one system supported valid time and exactly one system supported transaction time. As for valid-time relations and transaction-time relations, there are no restrictions as to how either of these temporal dimensions may be incorporated into the tuples."

In the current LADM standard (ISO-TC211 2012), VersionedObject is an abstract class, and in the same way the temporal relations in Figure 5 are abstract. In effect, this means they provide max and min timestamps to the real relations, but it is suggested that the Event classes be real tables (carrying the event metadata for the database changes – not shown in Figure 5). Where history is permitted to be corrected, the ValidEvent itself may be an object with DB history, but other implementations are possible - See (Thompson, van Oosterom et al. 2019). That is to say, the table of ValidEvents can be a TransactionTime relation.

The TransactionEvent should not have history, because the only option to change a transaction event should be to purge its results and resubmit them (and this can only be done if no later events have been recorded on the same base objects). It may well be, in any case, that the TransactionEvents are intended as an audit trail, in which case no modification can be permitted.

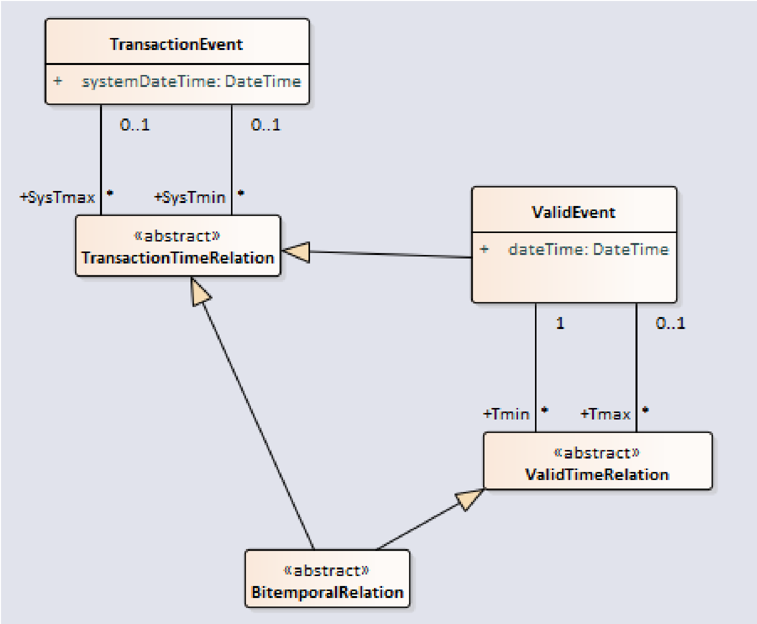

Figure 5 Bi-Temporal concepts.

3.1 Database Support

Bi-temporal support has been included in SQL11 (using the terminology Application_Time, and System_Time) (Kulkarni and Michels 2012). Temporal support is included in IBM DB2 (Saracco, Nicola et al. 2013); Oracle (Jernigan, Guo et al. 2009); and is available in PostGres (Clark 2015) although the implementations differ in nomenclature and details from the proposed SQL support. ESRI's Parcel Fabric has attributes "System Start Date" "System End Date" "Legal Start Date" and "Legal End Date" on the Parcels and Points tables (ESRI 2016).

The Land Administration Domain Model (LADM – ISO19152) (ISO-TC211 2012) potentially invites bi-temporal support. It specifies an abstract Versioned Object class with time stamps – covering the TransactionTime concept; while various tables record ValidTime events – such as LA_Source which records the date/time a spatial unit is changed. All changes that affect the spatial units in the cadastre should be recorded using a LA_Source object, which is directly linked to the geometric and other versioned objects by means of the lifeSpanStamp attribute "The moment that the event, represented by the instance of LA_Source, is further processed in the LA system (this is the moment of endLifespanVersion of old instances, and the moment of beginLifespanVersion of new instances" (ISO-TC211 2012 Page 15). In a similar way, LA_RRR records events that vary the relationship between spatial unit and party.

3.2 ACID (Atomicity, Consistency, Isolation and Durability) in History

The so-called ACID database concept is central to database design and construction. It is important it is not lost when historic data is retrieved. When data is retrieved as at some time in history, the mechanism is that constraints such as Tmin ≤ time < Tmax are included in the selection clauses of all temporal tables. This works well if all timestamps are quantised – such that all objects which are updated in a single transaction are stamped with exactly the same DateTime.

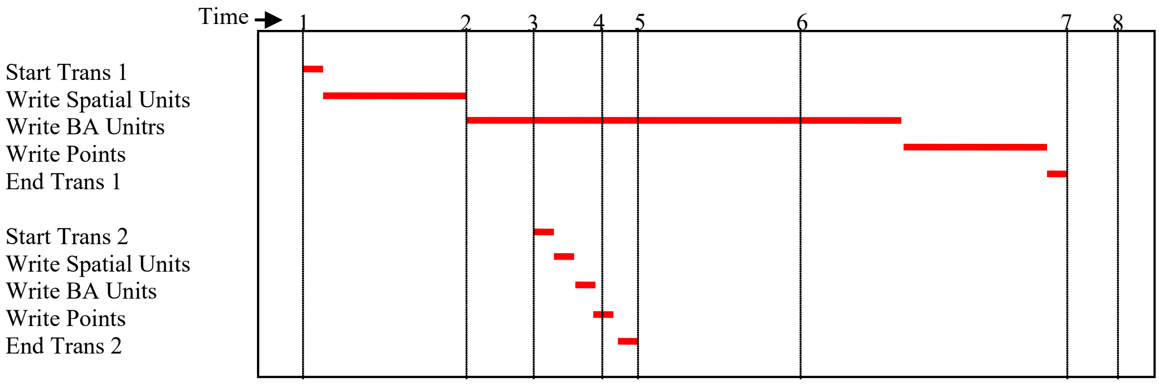

Figure 6 Two transactions being committed to the database at overlapping times

Consider the case of Figure 6. Transaction 1 is being written to the database when Transaction 2 starts to load. Unless "dirty read" is enabled, someone querying the database will see: Nothing updated (at time 4 or earlier); Transaction 2 committed (e.g. at time 6); Or both committed (after time 7). At no time will a user see a part completed transaction. This is important, because the references, including topology of the data may be invalid while a transaction is incomplete. (Some databases, for response reasons allow "dirty read" - which balances speed of access against the ill effects that partial transactions might cause).

Now consider the case where each TransactionTime object is timestamped at the time it is written or marked as retired. An enquiry made after time 8 "as at" time 4 (Figure 6) will retrieve Spatial Units from Transaction 1, but not the points that define them, and something similar for transaction 2. To prevent such issues it is necessary to determine a transaction time at the start of the transaction and use it for all the objects that are being updated. This means that an enquiry "as at" time 4 will see all of transactions 1 and 2 committed. This is rather paradoxical, because an enquiry in real time at time 4 will not see either transaction committed.

An alternate solution with much to recommend it is the concept of the eventID. A surrogate ID is created which becomes the timestamp in the TransactionTimeRelation, This ensures that for any two events a and b:

$$\text{a.eventID} > \text{b.eventID} \Rightarrow \text{a.systemDateTime} \geq \text{b. systemDateTime}$$
$$\text{a.eventID} = \text{b.eventID} \Rightarrow \text{a. systemDateTime} = \text{b. systemDateTime}$$
$$\text{a. systemDateTime} > \text{b. systemDateTime} \Rightarrow \text{a.eventID} > \text{b.eventID}$$

Note that in this strategy, it is possible for two events to be distinguished even though they have the same systemDateTime – i.e. they were committed within a shorter period than the granularity of the DateTime type. A further advantage of this strategy is that it provides a place (a TransactionEvent record) in which to store metadata of the update (who, why, etc.). Referring back to Figure 5, this approach uses surrogate eventIDs for the attributes SysTmax, SysTmin, Tmax and Tmin.

Note that versioned object in LADM v1 has attributes:

> quality: DQ_Element [0..*]
> source: CI_ResponsibleParty [0..*] (ISO-TC211 2012)

which allow the recording of update metadata (linked to each versioned object), and it is attributes of these types that would be recorded in the TransactionEvent table.

3.3 ValidTime Events

While some of the (TransactionTime) issues discussed in 3.2 also apply to the ValidTime events and relations, there are differences. Because it is likely that these events will hit the database in non-chronological order (there may be geographic parts of the cadastre which are more dynamic than others, and so the update cycle is faster – e.g. in an area of high development). Thus a sequential eventID is difficult to ensure.

Slotting in ValidTime events on a geometric object that already has later events can be difficult. It is essential that topology is maintained throughout the history, and that no earlier data is accidently allowed back into the later history. For this reason, it may be considered desirable that no out-of-sequence ValidTime events are permitted to be applied to any individual ValidTimeObject – that is out of sequence events are possible in different parts of the database, but not on a single object.

The same issue applies to updating the ValidEvent itself – particularly if the date is modified. It may be that only the most recent valid event for any set of objects can be modified, and only then if the action does not put it out of sequence with other events on any of these objects.

In the current LADM schema, much of this functionality is carried by subclasses of LA_Source, which record date and time, quality and responsible party metadata of the ValidTime event (ISO-TC211 2012).

4. CADASTRAL ENTITIES

The following point-like entities can exist in a cadastre, either as object classes or as attributes of other classes, depending on the design. The geometric attributes used to define these entities will depend on the SRS decision (See Section 2.1). Since most cadastral spatial units are defined as 2D, we begin with the entities that are needed for a solely 2D Cadastre:

Vertex2D: A corner or any point-like entity along a cadastral boundary – the junction of 2 or -more lines in a 2D spatial unit boundary. It could also be the end of a hanging line in a not-fully-validated data set.

Node2D: A point-like entity at which three or more cadastral boundaries meet. A Node2D is a Vertex2D. Typically a Node2D will be used in the encoding of topological connectivity.

Knot2D, Centre2D, Focus2D etc.: Point-like entities that are used in the parametric definitions of curves, circles and ellipses etc.

TraversePoint2D: A Point-like entity used in a survey when the actual point positions cannot be reached (e.g. edges of marshland). (See points 9-13 and points 5 and 8 in Figure 8)

SurveyMark2D: One of a series of physical objects that have been placed or identified to assist with the survey process. They may be permanent or temporary. (Examples: survey pegs, screw in concrete, building corner, permanent survey marks).

Generally speaking these point-like entities in a cadastre represent fiat objects, and occupy a PlateFixedPoint. That is to say the entity moves with the Earth's crust. Some entities that define a natural ambulatory boundary are only defined at a point in time, and occupy a PointInstant - they are tangible. SurveyMarks are tangible objects, and occupy a PlateFixedPoint. If a mark is destroyed and replaced at the same location it may re-occupy the same PlateFixedPoint. It is quite possible for more than one point-like entity to occupy the same PlateFixedPoint, although this would be unusual (see Figure 7).

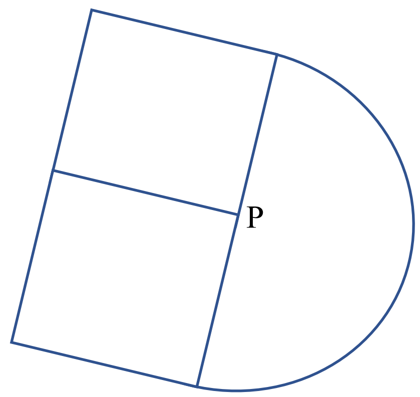

Figure 7 Point P is a Node in the boundary of the two rectangular spatial units, but the same location is the centre of the circular boundary of the half-moon shaped spatial unit.

Note that, even in a 2D cadastre, the Z value can be recorded and be significant. The distance between two points must allow for the fact that the vertical lines through two points diverge as Z increases. In a 2D Cadastre, the accuracy required of Z values is not high (tens of metres is OK), and a simple "approximate local ground level" will suit. Rather than record the Z value in the individual point records, an approximate DEM (Digital Elevation Model) or TIN can be used.

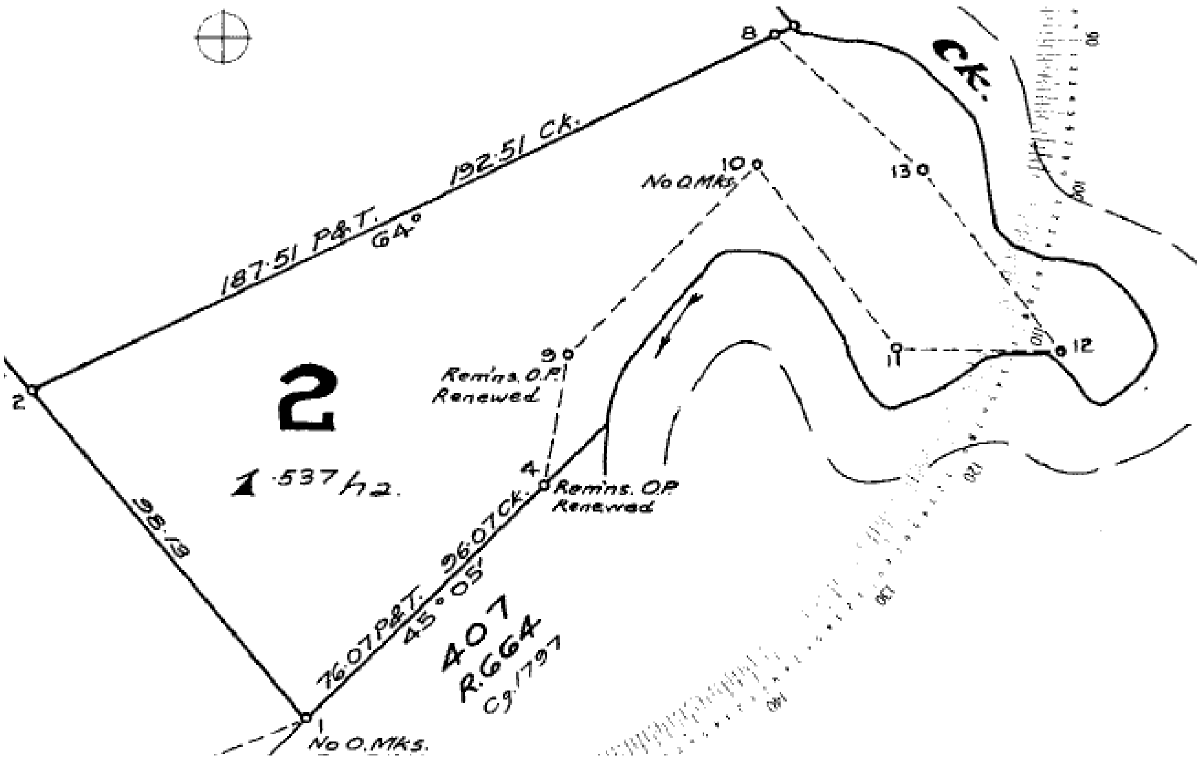

Figure 8 Various point-like entities. Point 2 is a Node2D. Point 8 is a Vertex2D, but not a node in the cadastral fabric. Point 13 is a TraversePoint2D. The curved line is composed of a large number of Vertex2D objects which are on a natural boundary at an instant of time (in this case the plan date 9th Feb 1981).

4.1 Moving into 3D

The aim is to develop a Cadastral database containing both 2D and 3D spatial units (not a separate 3D cadastre). It should be clear that the Z direction is a special case in Cadastre. The most useful definition in Cadastre is that the (x,y) coordinate values along a vertical line do not vary. To a high accuracy, this is also parallel to the direction of gravity. For this reason, a useful approach to 3D Cadastre is to build on the existing 2D Cadastre entities.

It is well recognised (Stoter and van Oosterom 2006) that a so-called 2D spatial unit actually defines a column of space above and below the ground level definition. The LADM defines the concept of LA_BoundaryFaceString (ISO-TC211 2012), which is in effect a GM_MultiCurve extruded vertically (above and below the definition level).

Thus, in Figure 9, the 3D spatial unit is first defined in plan, and then the 3D details are provided in an isometric drawing. There is also a table of points – for example Vertex2D 19 has two 3D locations defined as 19a and 19b (circled in Figure 9). The z values of these are presented in the table. In this discussion, the term Pole is used for Vertex2D and is equivalent.

PlateFixedPole: The pole defined by a PlateFixedPoint (x_0, y_0, z_0) – being the locus of all PlateFixedPoints (x, y, z) such that x=x_0, y=y_0, $-\infty < z < \infty$.

Vertex3D: A corner or any point-like entity on a cadastral boundary – the junction of 2 or more lines in a 2D spatial unit boundary, the point of meeting of 3 or more faces. Could also be the end of a hanging line or the vertex of a hanging face in a not-fully-validated data set.

Node3D: A point-like entity at which three or more cadastral boundary faces and lines meet. A Node3D is a Vertex3D. A Node3D may be useful in the encoding of topological connectivity.

Knot3D, Centre3D, Focus3D etc.: Point-like entities that are used in the parametric definitions of curves, circles and ellipses etc.

TraversePoint3D: A Point-like entity used in a survey when the actual point positions cannot be reached, or to connect two points that cannot be directly measured.

SurveyMark3D: A permanent or temporary survey mark can indicate a Z value.

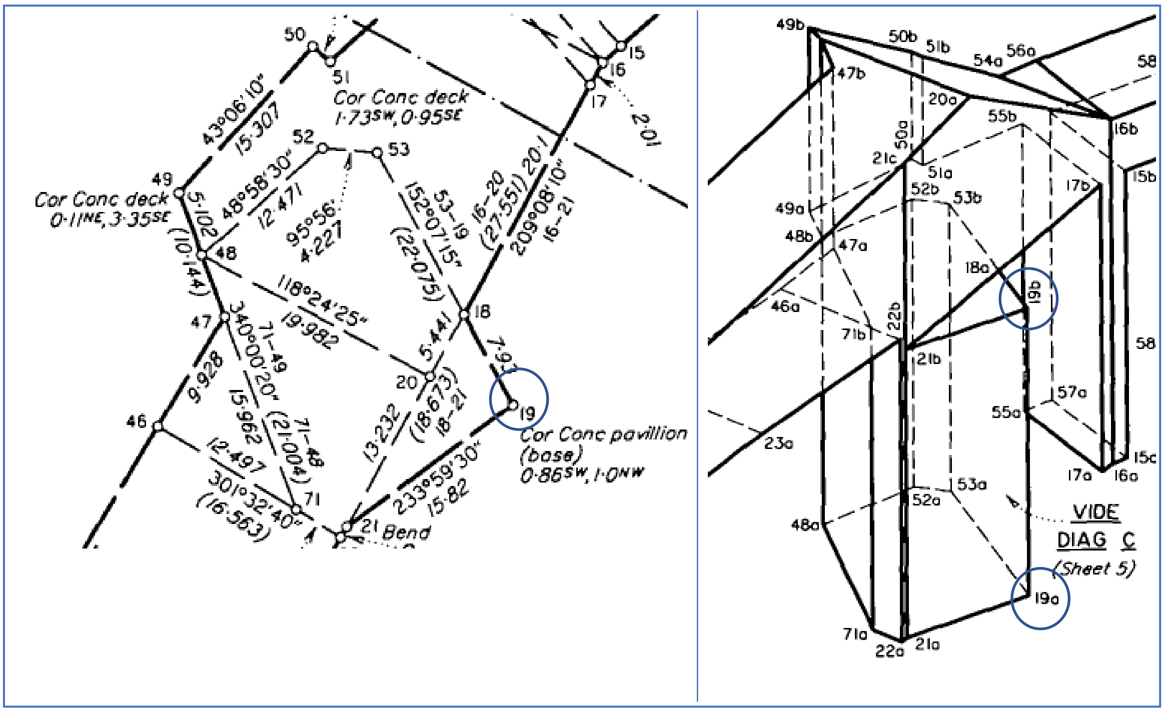

Figure 9 A 3D spatial unit defined first in plan (L) then in an isometric view (R).

The discussion of PlateFixedPoint, in Section 2.1, the actual movements considered were in the horizontal directions. Donnelly, Crook et al. restricted discussion to mainly 2D. “This paper does not further consider the vertical reference frame, except to note that analysis is required to determine how deformation modelling should be incorporated into a vertical reference frame, if at all, given that many engineering applications require that vertical deformation is visible in measurements.” (Donnelly, Crook et al. 2015 Page 236). In this paper, it is assumed here that the cadastre is defined in relation to the earth’s surface – plate movements below the surface are assumed not to affect the legal boundary, so we can proceed as if all plate velocities are independent of Z value. (If this approximation is not accepted, modification of the below argument will be necessary). To a good approximation, the velocities can also be considered independent of time. That is - let $\boldsymbol{v}(x, y)$ be a vector velocity function for any point instant $p(x, y, z, t)$; then $\boldsymbol{v}(x, y, z, t) = (v_x(x, y), v_y(x, y), v_z(x, y))$ defines the movement of the plate at point instant (x, y, z, t). Thus if a PlateFixedPoint P exists at instant t at point (x, y, z) in an ITRF (i.e. at point instant (x, y, z, t)) then at a later instant t', its coordinates in the ITRF will be:

$$x' = x + (t' - t)\, v_x(x, y),$$
$$x' = y + (t' - t)\, v_y(x, y),$$
$$z' = z + (t' - t)\, v_z(x, y)$$

4.2 Representable point

It must be recognised that the coordinates cannot be directly represented as real numbers. They may be stored as floating or fixed-point approximations (discrete, finite precision). There are many calculations that introduce errors by virtue of the limited resolution. These must be considered, and it must be born in mind that two different PlateFixedPoints can become entangled by rounding errors.

5. CONCLUSIONS

Existing definitions, and suggestions for basic terms for concepts relating to point-like objects (real-world, and representations) have been given, and discussed in relation to modification of information on those objects in adatabase. These have been further explored in terms of the concept of bi-temporal history. The extension of these techniques into three spatial dimensions has been considered.
It is suggested that the concepts discussed here, especially the issue of bitemporal history, and the concepts and terminology for point-like objects be considered for the upcoming modificatopms of the LADM.

5.1 Future Research

This research has been restricted to point-like objects (zero dimensional). This needs to be extended into other higher dimensional objects such as lines, surfaces etc. In particular, the boundaries of 2D and 3D spatial units need to be considered. For example, although a line can be modified by re-adjusting the coordinates of its end-points, if the accuracy of a cadastral line is to be improved, it may be necessary to create new "points" along the line (to take into account the curvature of the Earth's surface).

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BIOGRAPHICAL NOTES

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