Maintaining Cadastral Measurement Data In GIS

Tim HODSON, United States

Key words: land records, boundary network, cadastral measurements, parcel fabric

SUMMARY

The next generation parcel fabric technology allows cadastral organizations to store parcel-based measurement information as well as its metadata. Organizations that serve as the authoritative source for multi-purpose land parcel information systems require specific metrics on the captured data.

The technology innovations of the past two decades have had a major impact on speed, quantity, quality and overall characteristics of cadastral measurement data. Simple web maps on mobile devices can be used to capture high accuracy coordinate information in the field, either in real-time, or disconnected and synchronized later. Such innovations have spawned exciting new approaches in the cadastral information systems of developing nations around the world and have also sparked a resurgence in the modernization of cadastral systems in the developed world. As a result, there is now an ever-growing body of cadastral data coming from diverse sources ranging from recorded paper documents, to electronically submitted records, to a variety of measurement sensors.

The parcel fabric allows cadastral organizations to support fit-for-purpose requirements by storing the required metrics for establishing appropriate use. Metadata such as method of capture, date, spatial accuracy, and historical lineage can be stored, used and published as needed. The built-in data quality management of the software assesses other key criteria such as topology and attribute accuracy.

This paper describes a modern cadastral software system that is a proven, practical solution for maintaining and using measurement-based information for land parcels.

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1. INTRODUCTION

Representing land parcel information in a transparent public system is key to securing title and property ownership rights; a nation's economy is greatly influenced by the ability of its citizens to leverage the value of their land to gain access to credit. (De Soto, 2009)

Cadsastral authorities serving as the authoratative source for land information are required to maintain a seamless digital map for use as a spatial index to cadastral registration, taxation and titling systems. Contemporary systems often publish property information online as web services for use by the public and throughout government. The parcel base map layer commonly serves as spatial control in the maintenance of other GIS datasets, such as utilities, transportation, planning, and zoning. Location is the common key to bring together heterogenous systems. (Dangermond, 2019) The continued growth in technologies that spatially enable traditionally non-spatial datasets presents many potential new benefits. These benefits run the risk of not being fully realized if fit-for-purpose metrics are not defined and published with the data.

Securing title to land includes capturing location evidence, usually by a partial or complete delineation of boundaries with accompanying description of physical features and, or, reference to abutting properties. The type and method of capture for boundary delineation evidence varies around the globe. From an information management perspective, as older titling systems adapt to newer technologies, they carry forward the approaches from the past in their natural evolution. Consequently, the capture and management of boundary evidence have evolved into different models, albeit with the underlying measurement types (distances, angles, etc.) having the same meaning in all models. Boundary evidence may directly reference physical features that depict the boundary itself, such as stone walls, hedgerows, etc. as in the general boundaries model; or may include distance measurements offset from existing structures near to the boundary, as seen in European countries (Hagemans, 2017); or may be defined by physical monuments placed in the ground to define each bend in a boundary line, along with the distances, angles, and directions between, and the descriptions of the marks placed. Devices used have varied in sophistication through time, ranging from chain, to tape measure to total station, to real time kinematic GNSS. Of course, the recording medium of these measurements have also changed through time so that although a specific measurement type may be a "simple horizontal distance" for example, the resulting digital representations in modern systems range from scanned file images of the original hand-written field sketches (ibid), to electronic field books, to a record stored in a geodatabase table.

The old measurements are used to relocate recorded boundaries, and new surveys attempt to find and reference the same physical objects that were referenced in older surveys. The result is a measurement network of mixed measurement types, ages, and accuracy.

This paper reviews the general measurement concepts for building a cadastral map and describes the ArcGIS Pro technology in the context of these concepts.

2. MEASUREMENTS: COORDINATES, ANGLES, DISTANCES AND DIRECTIONS

Coordinates are traditionally not considered to be measurements per se, because in coordinate geometry systems (COGO) distances, angles and directions are used to calculate new coordinates rather than the coordinates being used to generate measurements. However, it is typical for surveyors in the US to produce and submit digital representations of parcel (and other) data in a ground coordinate system, where the intent is for the computed distance between any two points in their CAD drawing to represent the "true" horizontal ground distance as would be measured between the same two physical locations in the field. In GIS datasets the map projection is referenced to the ellipsoid and projected to "grid." This means that when these CAD files are brought to the GIS they are offset because of the scale factor applied to the coordinates. (Figure 1.)

Figure 1. Ground Coordinates versus Grid Coordinates

While there is a subtle distinction between coordinates resulting from measurements versus coordinates *as* measurements, ground coordinate systems allow for computed line lengths between coordinates to derive ground distance measurements.

The documents recorded by US surveyors include statements that allow the plan to be "calibrated" to a specified projection; this metadata is called the ground to grid correction, and has two parts, the combined scale factor, and the basis-of-bearing. The combined scale factor relates the projection on the ellipsoid back to the ground. It is applied to distance measurements and combines the scale factor attributed to height above sea level with the scale factor resulting from the projection's distortion at the location of the plan. (Doyle, 2010)

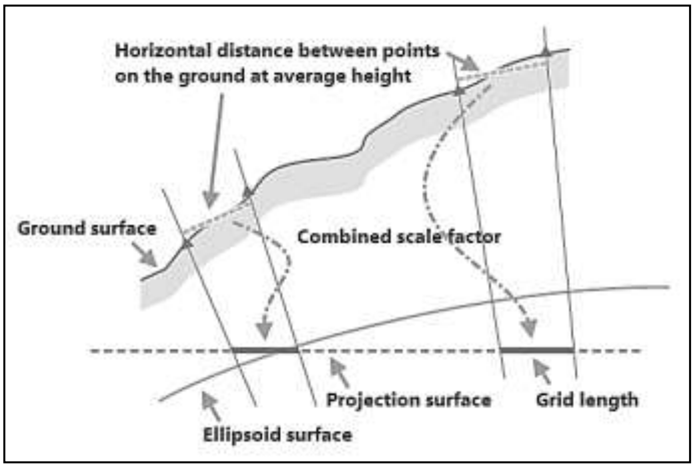


Figure 2. Combined scale factor

The basis-of-bearing references a known physically marked ground line, and states the bearing adopted for that line. This is the baseline for all bearings on the plan and allows a rotation-to-grid to be computed for any projection. Regardless of the stated basis-of-bearing, the difference between any two bearings on the same plan gives us an angle measurement with good relative accuracy on the ground. (Figure 3.)

The angles derived from these sets of directions may be used in least squares adjustment as measurements in the measurement network.

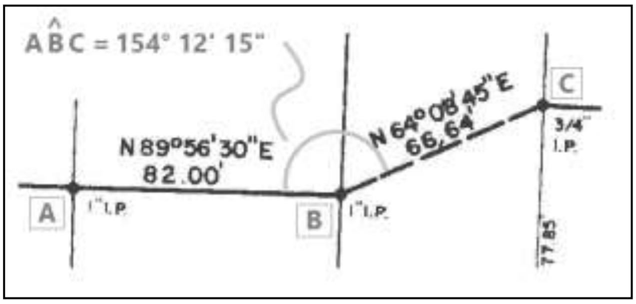


Figure 3. Angle from two directions

Together these angles, directions, and ground distance measurements provide independence from a specific projection. This means that the same ground values can be recorded in a database table as static numbers that are not tied to any projection. The distances recorded on plans and in deed descriptions in the USA are universally accepted to represent horizontal ground distances. (Brown, et al 1994.) These are the cadastral surveyor's instructions for finding the original physical marks that define property boundaries.

Geodatabase tables that store vector geometry, known as *feature classes* are presented on the map as *feature layers*, and the individual table rows are called *features*. In 2019 Esri enhanced the ArcGIS Pro technology, introducing the new *Parcel Fabric*. The ArcGIS Pro Parcel Fabric is modeled with a group of feature classes as further described in the following sections.

Mapped lines representing boundaries are stored as line features in the parcel fabric. Using distances as an example, the legally documented value for a specific boundary line is stored as an attribute on the feature. The geometry shape length is also stored as a separate property of the line feature. The shape property is dynamic and is designed to be allowed to change by user workflows; it is system maintained. By comparison, the stored record distance value may only be changed directly by the user and is never automatically changed by the system. It is changed by a user if for example a mistake is found, and the value needs to be explicitly updated to match the legal record.

Changes to the mapped shape length of these lines occur as the result of editing workflows such as integrating new data into pre-existing parcel base or recomputing the

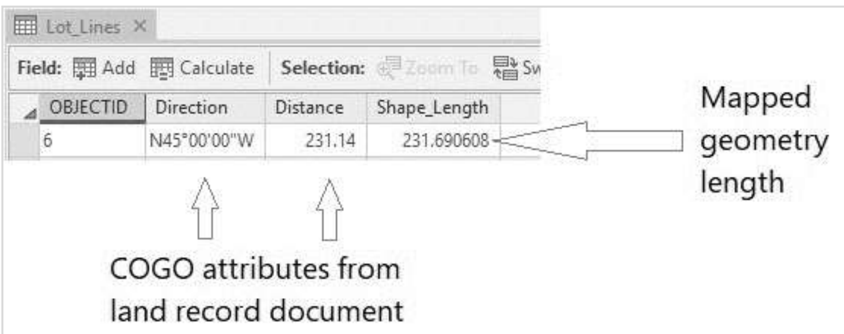


Figure 4. Entered land record versus dynamic mapped geometry

measurement network through least squares.

3. CONFIGURABLE SYSTEM OF RECORD

The architects of land information systems require the ability to build technology solutions that are easily configured without the need to create customized tools, and yet flexible enough to accommodate the business needs of their client. Pre-configured solutions available with off-the-shelf software products are more easily adapted to the varying business needs of different land records systems.

Maintaining data quality in information systems requires avoiding the deterioration of data quality during regular maintenance workflows, or when migrating data from old to new systems.

The term "accuracy" is used broadly and has varied meaning and context. Geographic information systems have additional spatial quality considerations. The different categories of spatial and non-spatial qualities are: attribute accuracy, topology, relative accuracy, and ground-truth accuracy. Ground truth accuracy has two elements, the first is the absolute coordinate accuracy relating to how well the coordinate stored in the mapping system matches the "absolute" survey-measured coordinate returned from the field. The other element is related to identification of the correct object in the field and confirming the correct description stored in the system for the represented feature. This may be characterized as ensuring that you did not "accurately measure the wrong feature."

Relative accuracy describes the local spatial relationship between geographic features; for example, a road right-of-way may be described as 60 feet wide such that two parcels on either side of the road are mapped with a 60 foot separation. If the digital representation of these two parcels are repositioned or given an identical X and Y offset, their relative accuracy is unchanged whereas the absolute positional ground truth is altered.

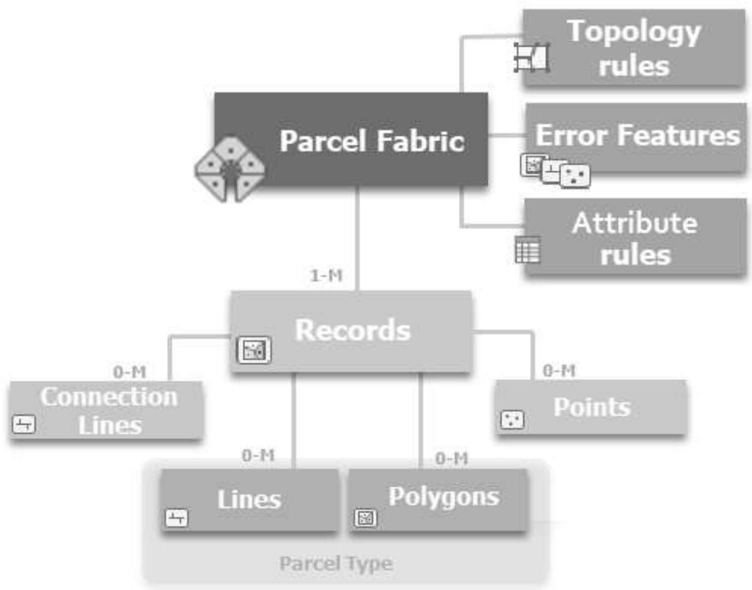
The accuracy types are co-dependent and build on each other. For example, the stored attribute for a horizontal distance is used to compare with the mapped shape length to assess if the difference is significant, and may signify a distorted geometry, or alternatively may signify a mistake in the distance attribute. The legal date attribute may be used to understand the likely method of capture that in turn influences how the measurement is used in adjustment techniques. The date also has added significance when considered in the context of dynamic datums.

In ArcGIS Pro, a configurable set of frameworks is available to apply these different types of quality assurance checks. They are broadly available as part of the overall system of record in the ArcGIS eco system and are built into the parcel fabric dataset technology. There is a framework for *Attribute Rules*, and for *Topology Rules.* The topology and attribute rules are pre-configured for the fabric dataset and additional rules can be added by land information system architects. (Brinkman, 2021)

In ArcGIS Pro the quality checks for attributes can be implemented by leveraging the Attribute Rules framework. This configurable environment provides the ability to do immediate quality checks at the time of data edits, and either prevent an edit (*Constraint* rule) or write new metadata information (*Calculate* rule) based on the criteria configured for the rule. There are also *Validation* rules; these are evaluated directly by the user on demand, and any attribute criteria that are not valid are reported as *Error Features* that can be inspected by the user so that further action can be taken to re-assess the attribute quality; the attributes are fixed, and the user re-evaluates the rules to confirm the error features are removed. (Ibid)

The frameworks for Topology and Attribute Rules work in a similar way, and these are reviewed in the next section.

4. PARCEL FABRIC MODEL



The ArcGIS Pro Parcel Fabric is a controller dataset that includes: a set of simple feature classes; a geodatabase *Topology* and *Attribute Rules*.

The *Records* feature class stores the representation of each recording document that brings new parcels into the fabric. These documents may represent one or multiple parcels, and the associated transactions also retire the parent parcels. These parent parcels are not removed and contribute to the parcel lineage. Each Record feature has a polygon footprint of the fabric features that it holds. This polygon feature in the Records feature class is system managed.

Multiple parcel types can be added to a fabric. Each parcel type is represented by a pair of feature classes, *Polygons* to store polygon features, and *Lines* to store the line features. The feature class pair is associated with the same parcel type. A parcel type is created with a given name such as 'Tax' or 'Lot', for example. These feature classes have a pre-defined set of attribute fields and they can be extended with additional fields, domains and subtypes.

Parcel boundaries are stored in the *Lines* feature class. The line feature classes in the fabric are automatically *COGO-enabled* for all parcel types. This means that they have additional attribute fields to store values from cadastral documents, such as the directions, distances for straight-line boundaries, or radius and arclengths for circular arc boundaries. It is also possible for these fields to be empty if one or all the values are not on the original document. Most COGO-lines are expected to be two-point, single-segment lines though there are exceptions such as natural boundaries like rivers and shorelines. Since parcels are usually defined by a closed loop of two-point lines that store dimension information, a mathematical misclosure can be computed and stored on the polygon feature and provides a quality check on the line dimensions.

The *Connection Lines* feature class is used to store any type of line that is not used as part of a parcel boundary. They store recorded dimensions for lines that connect between parcels or that connect to control points. Some examples are street centerlines, and tie lines.

The *Points* features are used to define a network topology. They have a mapped geometry location stored in the *Shape* field. The attribute fields include *Name*, *X*, *Y* and *Z* fields to optionally store coordinate attributes to complement the mapped geometry. Values in the *AccuracyXY* and *AccuracyZ* fields are used in least squares analysis and adjustment. The feature geometry for all data, and the coordinate attributes stored on points are based on the spatial reference of the fabric dataset. Points can be set as *fixed* and are used as constraints in a least-squares adjustment. Each parcel corner is represented by a single point feature in the point feature class and connects multiple measured lines in the network. These lines may come from different cadastral records recorded with different dates. A reference to the originating document provides information about the recorded date of each line.

Figure 5. Parcel fabric topology rules for a parcel type called "Lot"

The *Topology* in a geodatabase is a set of rules that define how features are spatially related. In the parcel fabric these rules are used to define the connectivity in the network of parcel boundaries and to define the divisions between adjacent parcel polygons without gaps or overlaps along parcel boundaries.

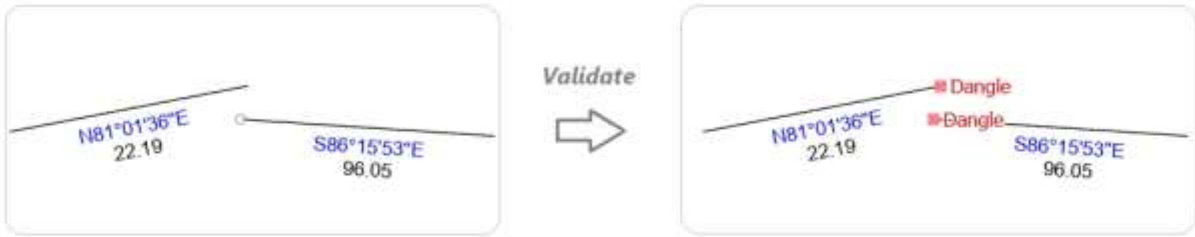


Figure 6. Parcel lines not connected at a point or another parcel line's end result in point error features called Dangles

The locations of edits made by users are tracked by the system, and when the user is ready, they can use a validate command on the topology to make sure that none of these rules have been broken. If a rule is broken, then *Error Features* are created and displayed on the map. These are used to draw attention to data errors so that they can be fixed. (Figures 7 and 8)

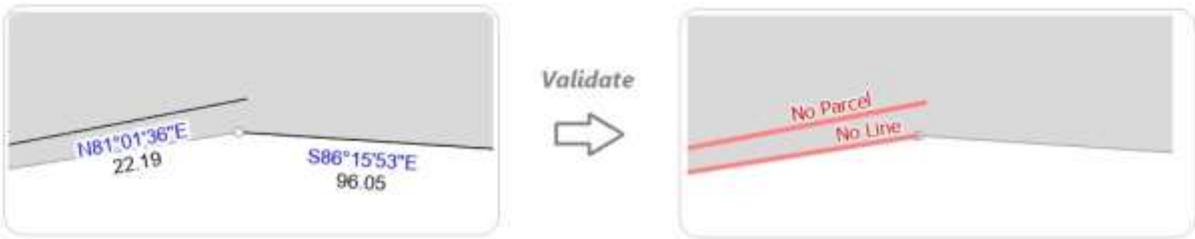


Figure 7. for a parcel type, polygon edges with no line, and lines not on a polygon edge produce line error features

Attribute rules are included as part of the parcel fabric dataset. For example, there is an attribute rule that states that parcel features must be assigned to a record. You can opt in or opt out of the given rules by turning them on or off, and you can also configure your own. (Esri, Documentation Reference 1)

5. PARCEL EDITING CONCEPTS

When editing a parcel fabric there are two types of workflows: *record driven* workflows, and *quality driven* workflows.

5.1 Record driven workflows and the Active Record

The two parcel type feature classes, the points, and connection lines feature classes all have attribute fields to reference a globally unique identifier (*guid*). Record driven workflows update the legal parcel information, and the parcel lineage; the parent parcel is retired when its child parcels are created. This happens when entering data from a legal land record document such as a Deed, Subdivision Plan, Record of Survey, and so on. For example, when an existing parcel gets subdivided into two portions, the division occurs because of a legal document. The original parent parcel is retired by, and the two new parcels are created by that legal record. From the user workflow perspective, the first step is to create the record in the fabric and then to set it as *active*.

The active record's globally unique identifier is used to populate the fields called *RetiredByRecord* and *CreatedByRecord*. These fields are populated when new parcel fabric features are created, or when existing parcels are retired and are being replaced by new parcels. When the active record is set, the edits that create new parcel features are tagged with this active record's guid, and parcel lineage is captured as in the above subdivide example.

5.2 Quality driven workflows

The quality driven workflows are used for making edits to fix reported data problems found via topology or attribute rules. This may include attribute edits, such as correcting a parcel's name, its stated area, or the attributed distance on its boundary line. These quality driven workflows can also be geometry based such as re-aligning parcel boundaries. In general, quality driven workflows do not require an active record to be set. If an active record is set for the map it will have no impact on the quality driven workflows, since they are edits to existing features and are not creating new features.

6. EDITING VIA PUBLISHED FEATURE SERVICES

Though system architects are conerned with configuring the land information geodatabase, ArcGIS Pro is designed to easily and seamlessly work in a multi-user environment that is abstracted from the underlying data structures. This allows the users to focus on the features and interact with the feature layers in the map, without needing to know how and where the data is hosted. The land records professionals who manage the data through ArcGIS Pro sign in to a portal connection, and then connect to the parcel fabric feature service that is managed in a service oriented architecture. (SOA) The user creates a *version*, performs their edits, and then reconciles and posts their changes to make the updates through these services.

Although ArcGIS Pro is the primary client of these services, they are also avilable to thin clients allowing immediate access to the system through mobile devices in the field. New measurements and other relevant cadastral data can be captured by field crews and assessed in real time in the office, saving repeated return trips to the site. Where the infratructure does not support a real-time environment, or business requirements preclude it, the data can be captured in the field and synchronized later. (Bar-Maor, 2021 , Brinkman, 2021)

The *branch versioning* model used in this feature service editing model allows the dynamic changes to the fabric coordinate positions to be recovered from any previous *moment* in time; this means that the previous and current positions of fabric points can be used to maintain spatial relationships with features in other non-parcel layers, such as utilities that are located at known offsets from boundary lines. (Ibid)

7. DYNAMIC DATUMS

Unlike ground measurements, coordinates are dependent on specific spatial reference information, with a datum, epoch and projection. Due to tectonic changes coordinates change with time, and dynamic datums such as ITRF2020 model these tectonic changes. These models allow representing points with a velocity, thereby providing the calculation of their positions at specific dates. (Figure 9.)

When considering evidence of location for cadastral boundaries, there is an evidentiary hierarchy with certain forms of evidence holding precedence over others.

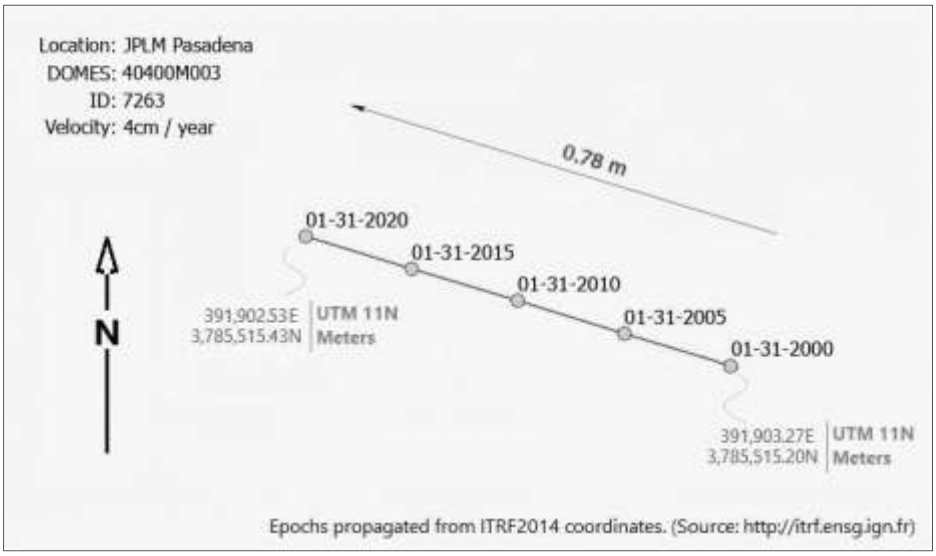


Figure 8. Changing position of a point in Pasadena, California.

For example, if a physical monument is found undisturbed and with the same physical characteristics as described in the legal record, then it holds precedence over the recorded measurements that were used to locate the mark. If no physical mark is found, or if it has been significantly disturbed, then the next strongest piece of evidence may be bearings and distances. These rules of evidence vary by country and jurisdiction. (Brown et al, 2010)

SUB-DIVISIONAL DIAGRAM Sheet 1 of 3 sheets

SIDES Metres		ANGLES OF DIRECTION		CO-ORDINATES Y System: Lo. 31°	X	S. G. No.
		Constants:		0,00	+3200 000,00	2471 / 1990
AB	45,29	336 12 40	A	− 1 005,05	+ 92 427,60	Approved
BC	55,92	0 31 50	B	− 1 021,86	+ 92 469,65	
CD	55,11	2 13 20	C	− 1 021,35	+ 92 525,57	
DE	39,61	358 05 30	D	− 1 019,21	+ 92 580,64	for
EF	15,59	350 38 50	E	− 1 020,53	+ 92 620,23	SURVEYOR-GENERAL
FG	45,72	336 04 10	F	− 1 023,06	+ 92 635,62	
GH	35,00	321 44 00	G	− 1 041,61	+ 92 677,41	1990-09-20
HJ	[illegible]	316 21 00	H	− 1 063,28	+ 92 704,89	
JK		313 [illegible]	I	− 1 105,24	+ 92 748,87	
K'				− 1 142,31	+ 92 784,32	
				174,02	+ [illegible] 817,22	
		50/2931	Δ	− 2 790,51	+ 92 895,32	
		289/2931	Δ	− 256,38	+ 93 454,36	

The figure represents ABCDEFGHJKLMNPQRSTUVWXYZA1B1C1D1E1F1G1H1J1K1L1M1 8,9345 Hectares of land being

SUB 15 OF THE FARM CIL No. 15301

situate in the City of Durban, Administrative District and Province of Natal

Surveyed in December 1976 – June 1990 by me,

H. E. Harvey
Professional Land Surveyor

This diagram relates to No.	The original diagram is	File MF
CET 6/11/1991	S. G. No. 2777/1977	S. R. 1930/1990 FU - 7A - 1A1
	C. C. T. No. 10371/1979	Comp. FU - 7A - 1A3 FU - 7A - 1A4
Registrar of Deeds	Grant	Deg Sheet 59

Figure 9. Portion of Sub-divisional diagram depicting coordinates in a static datum.

In some countries all the coordinates are recorded on the titling document. In the case of southern African countries this system of recorded coordinates predates GNSS and dynamic datums and so references a static datum. (Figure 10.)

Some studies have explored the idea that since dynamic datums are now able to represent four-dimensional coordinate representations, that they may be used as absolutes in the cadastral framework. In such a coordinate-based cadastre, the coordinates would be promoted to the same level of evidence as the physical feature itself.

At the individual parcel document level, the typical tectonic shifts do not alter the relative location between the physical ground locations of the boundaries; hence recorded coordinates like those in figure 10 continue to have the same value as evidence of boundary location, despite tectonic changes. (Horwood, 2012)

8. PARCEL BOUNDARY LINES AS A MEASUREMENT NETWORK

Although there are some exceptions for cadastral documents from the 1800's and early 1900's, the dimensions on a plan are not directly observed in the field and are instead derived by calculation from field measurements. It is also common for the boundaries on a plan to be pre-defined prior to physical marks being placed in the field. Since these dimensions are somewhat removed from the original measurements, there is some nonconformity in using a least-squares adjustment for parcel boundaries and in treating them as a measurement network. It is more conventional and would be a preferred if a network of GNSS baselines combined with total station measurements and other direct terrestrial measurements were used, but this information is typically not directly available in land information systems. Applying a least squares adjustment on large parcel networks with data of varying accuracy has been a technique employed by municipalities in Canada (Horwood et al, 2017) and Australia (Sandy et al, 2014), and by Bureau of Land Management in the USA. (BLM, 2001)

9. SOFTWARE COLLABORATION

Starting with ArcGIS Pro version 2.6, the parcel fabric technology includes a least-squares adjustment engine called *DynAdjust*, from Geoscience Australia. This engine was used for the development of the GDA2020 Australian reference frame and became widely available as an open source product in August 2018. (Fraser et al, 2018) Esri has integrated this technology for use with the parcel fabric and collaborates with the community of developers on the open source platform. The ArcGIS Pro .Net SDK (software development kit) is also available to third party developers to integrate with alternate engines, if needed. (Esri, Documentation Reference 2)

10. LEAST SQUARES ADJUSTMENT

The publicly recorded documents of boundary delineation are usually the best available evidence for subsequent surveyors to relocate parcel corners. When this data is properly maintained and modeled, least-squares analysis and adjustment provide the following benefits: discovery of outliers and mistakes in measurement data, validation of control points, accuracy estimates, and lastly, a best-fit estimate of the coordinate locations.

The least-squares adjustment does this analysis by using the connectivity of lines that are connected at shared points and leverages the resulting redundancy to determine a best-fit for the geometry of the network based on the stored COGO attributes on the lines, and the positions of constrained points. The lines can be given different standard deviations based on the date and methods in use at the time the original survey plan was submitted.

Certain points in the fabric can be constrained as fixed control points. Point coordinates may also be used as "floating control" in a *weighted* least-squares adjustment and these too can be assigned different accuracies, based on the method of capture. (Fraser, et al, 2019) For example, a point may be captured by using a heads-up digitized position taken from a fence corner visible on orthophoto imagery. This point would be given a lower accuracy estimate but may be combined with higher accuracy control points in the same adjustment process. (Horwood et al, 2017)

The adjustment estimates coordinate positions only and does not change the original COGO attribute values. These improved estimates of coordinate locations work towards the goal of achieving improved ground truth accuracy for the mapped parcel geometry, and of providing metrics about the reliability of these positions.

10.1 Free network adjustment

The adjustment engine can be used to check the consistency of COGO attributes without the influence of any control point constraints. This technique is called a free network adjustment and is used to detect potential mistakes in the entered dimension values for lines. These are reported as the outliers returned from the adjustment analysis. This technique can be used during an electronic submission of a subivision plan, for example, in order to confirm that there are no mistakes in the COGO attribute information.

10.2 Visualizing fit-for-purpose

The power of GIS layers rests in their ability to visually present complex attribute and spatial information in a meaningful way that is quickly and easily understood. The adjustment analysis produces a lot of valuable information that can be presented on a parcel map with different symbols and labels depending on the scale of the map. These scale-dependent views update dynamically as the user zooms in and out to varying scales in different map extents.

This provides contextual, scale-relevant visualization information about accuracy at a range of map extents from the entire dataset, to subdivisions, to individual parcels, to much larger scales showing individual parcel corner point features.

For example, a visual heat-map of accuracy for a large area of a city offers a powerful tool to help understand where additional measurement data or control points are needed. (Horwood et al, 2017, Figure 11.)

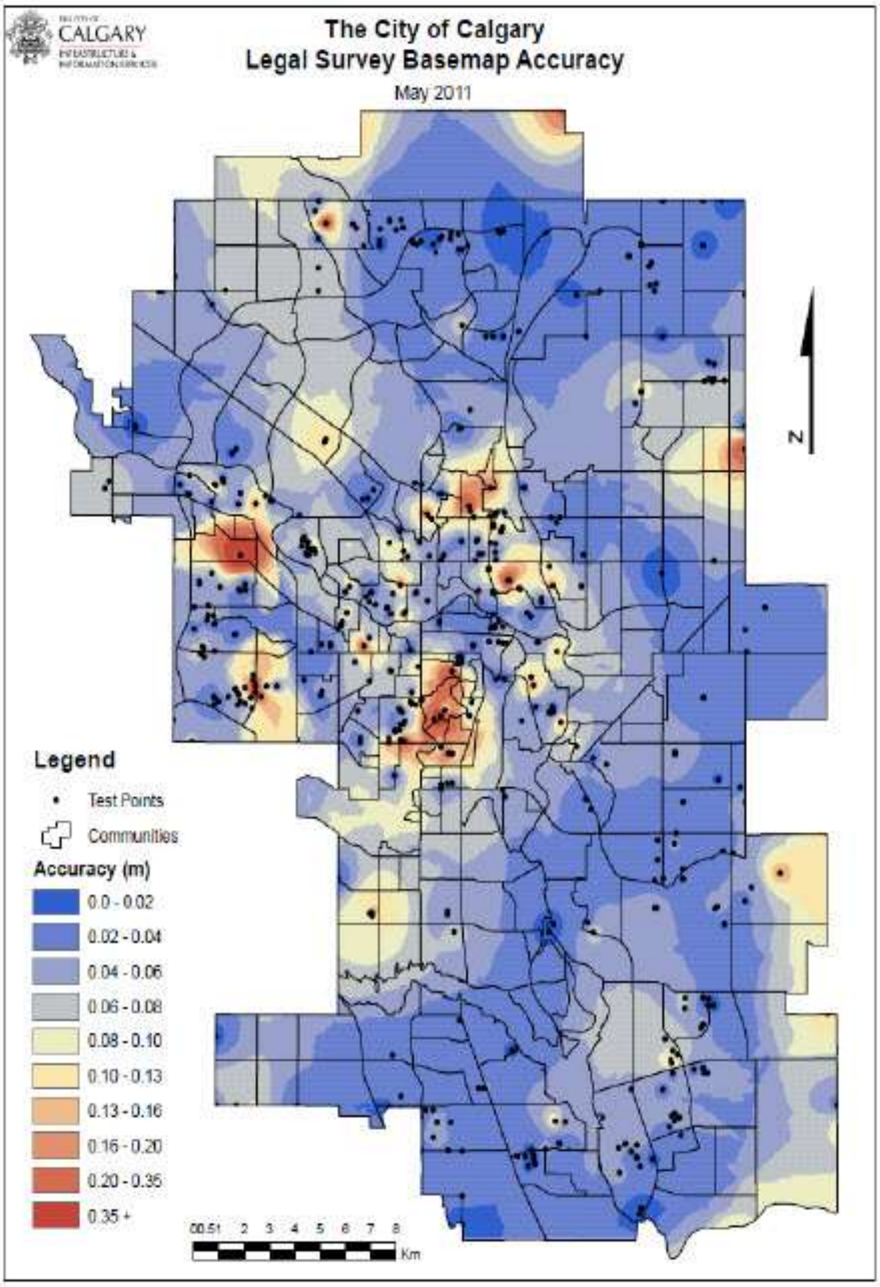
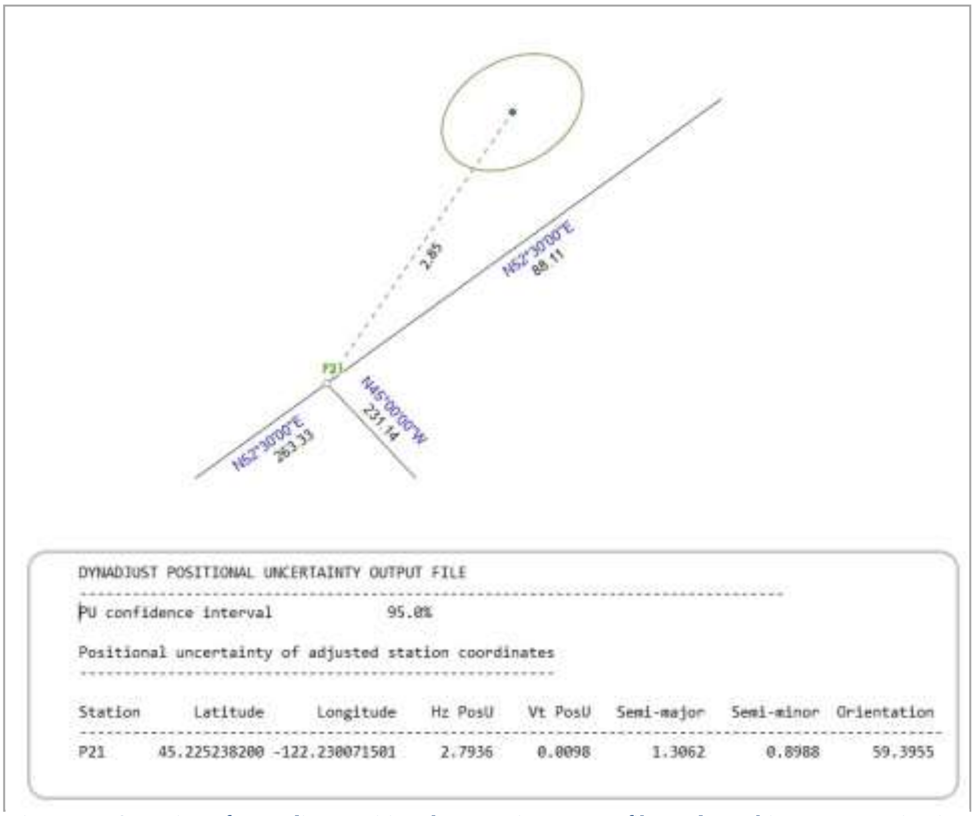


Figure 10. City-wide accracy heat map (Horwood, et al, 2017)



DYNADJUST POSITIONAL UNCERTAINTY OUTPUT FILE

PU confidence interval 95.0%

Positional uncertainty of adjusted station coordinates

Station	Latitude	Longitude	Hz PosU	Vt PosU	Semi-major	Semi-minor	Orientation
P21	45.225238200	-122.230071501	2.7936	0.0098	1.3062	0.8988	59.3955

Figure 12. A portion of Dynadjust positional uncertainty output file, and graphic representation in ArcGIS Pro (prototype)

11. CONCLUSIONS

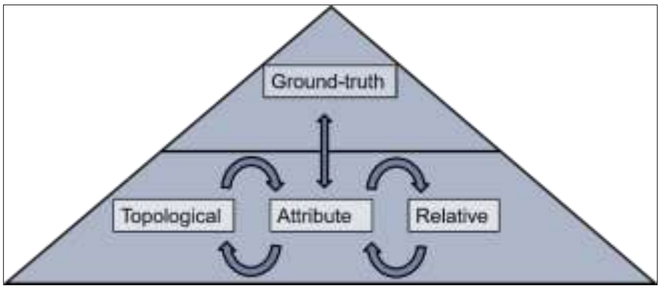


Figure 11. Accuracy types

Coordinate accuracy is a metric of how well a published coordinate matches the ground truth position of the feature that the coordinate represents. In many respects a published coordinate is secondary to knowledge about its accuracy. This understanding of ground truth accuracy makes spatial data considerably more useful to all consumers. Given the coordinate of a physical feature, information about its source and accuracy are required to make an informed decision about its potential use. This paper reviewed the different inter-related categories of accuracy, including topology for network connectivity, correct measurement attributes from original land records, the relative accuracy inherent within discrete cadastral records, and the ground-truthing of additional measurement and identification information from the field that is added through time. When combined into a cohesive information system it is possible to achieve continuous ground-truth improvement of the whole system over time, including enhanced information about the positional reliability of features.

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CONTACTS

Tim Hodson
Environmental Systems Research Institute
Address 111 Market Street NW, Suite 250
City Olympia
COUNTRY USA
Tel. +1 360 754 4727
Email: thodson@esri.com
Web site: www.esri.com