Modelling the Spatial and Temporal Resolution of a Sensor Observation

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Abstract

This paper looks at possible ways of modelling the spatial and temporal resolution of a sensor observation. A receptor-centric definition of spatial and temporal support is proposed, and it is suggested that spatial resolution can be equated with the spatial support of the observer, while temporal resolution can be estimated using the temporal support of the observer. A formal specification in the functional language Haskell helps to test the consistency of the ideas proposed.

1 Introduction

Resolution, the amount of detail in a representation, is an important aspect of geographic information, and different works (see for example WORBOYS 1998, STELL & WORBOYS 1998) have attempted a formal characterization of this unavoidable limitation of geographic datasets. Yet, as DEGBELO & KUHN (2012) indicate, there is currently no formal theory of resolution of observations underlying geographic information. The Open Geospatial Consortium (OGC) defines an observation as "an act associated with a discrete time instant or period through which a number, term or other symbol is assigned to a phenomenon" (PERCIVALL 2008). The importance of the notion of observation has been acknowledged in the literature[1], and the numerous examples of use of the observation ontology of the Semantic Sensor Network Incubator Group[2] indicate the importance of observation-based ontologies for the Semantic Sensor Web.

This paper adumbrates an observation-based theory of resolution. The theory is proposed as an ontology, and this has two main advantages: (i) conceptual clarification, and (ii) the theory can be implemented and processed by machines by means of ontology encoding languages such as the Web Ontology Language. The scope is limited to a *single* sensor observation, and to the spatial and temporal components of geographic information. The

[1] FRANK (2003) states for example that "all we know about the world is based on observation"; ADAMS & JANOWICZ (2011) point out that the geosciences rely on observations, models, and simulations to answer complex scientific questions such as the impact of global change.
[2] See examples of use in COMPTON et al.(2012).

Jekel, T., Car, A., Strobl, J. & Griesebner, G. (Eds.) (2013): GI_Forum 2013. Creating the GISociety.

functional ontology of observation and measurement from KUHN (2009) is used as starting point and briefly introduced in Section 2. The terms of the observation-based ontology of resolution are outlined in Section 3. The ontology is formally specified using the functional language Haskell (Section 4), and Section 5 concludes the paper.

2 Observation Ontologies

There are several proposals for observation ontologies (see for example (PROBST 2006; MADIN et al. 2007; JANOWICZ & COMPTON 2010; COMPTON et al. 2012)), but the functional ontology of observation and measurement (hereafter called 'FOOM') from (KUHN 2009) is chosen as a starting point because it possesses the following characteristics:

- Neutrality between field-based and object-based views which are the two main ways of conceptualizing geographic reality in GIScience;
- Account for humans as sensors, which are the key to process Volunteered Geographic Information as defined in (GOODCHILD 2007);
- Account for the two connotations of the term 'observation', namely the process of observing and its result.

The functional ontology of observation and measurement was aligned to the foundational ontology DOLCE and formally specified using the functional language Haskell. As a result, the extension to be proposed in Section 3 will also be aligned to DOLCE, and formally specified in Haskell. A presentation of DOLCE can be found in (GANGEMI et al. 2002; MASOLO et al. 2003), and examples of use of Haskell as formal specification language appear in[3] (FRANK 2003; WINTER & NITTEL 2003).

FOOM has five core concepts: *observable, stimulus, observer, observation value,* and *observation process*. The *observable* is the physical or temporal quality[4] to be observed; the *stimulus* is a detectable change in the environment; the *observer* is someone or something that assigns a symbol to the observable; the *observation value* is the outcome of the *observation process*. For the remainder of the discussion, the term *observation* will be used to denote the *observation value*, and the term *particular* will be used to refer to the *observed entity*[5]. The new terms specific to resolution are highlighted using a **bold font** in the next section.

3 Resolution of a Sensor Observation

In line with DEGBELO & KUHN (2012), resolution is viewed as a property of a representation. On that account, two terms are introduced: **spatial resolution**, and **temporal resolution**. The **spatial resolution** is the amount of spatial detail in an observation, and the **temporal resolution** is the amount of temporal detail in an observation. There are at least two ways of modelling the spatial and temporal resolution of an observation.

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[3] This list does not intend to be exhaustive.

[4] A quality is "any aspect of an entity (but not a part of it), which cannot exist without that entity" (see http://ontologydesignpatterns.org/ont/dul/DUL.owl; last accessed: January 31, 2013).

[5] The *observable* inheres in the *particular*.

3.1 Modelling resolution: the property-centric approach

FRANK (2009) points out that a sensor always measures over an extended area and time, and termed this extended area or time, the 'support' of the sensor. Hence, two terms can be introduced: the **spatial support** of the observer, and the **temporal support** of the observer. A general definition of support is: "[t]he size, geometry, and orientation of the space on which the observation is defined" (ATKINSON & TATE 2000); or alternatively "the largest time interval [T], area [L^2] or volume [L^3] for which the property of interest is considered homogeneous" (FINKE et al. 2002). Consequently, the **spatial support** is the area or volume for which the property of interest is considered homogeneous, and the **temporal support** is the largest time interval for which the property of interest is considered homogeneous. The **spatial resolution** of an observation can be equated with the **spatial support** of the observer, and its **temporal resolution** with the **temporal support** of the observer participating in the observation process.

3.2 Modelling resolution: the receptor-centric approach

After KUHN (2009), the observation process can be conceptualized as consisting of four steps (the first two steps are required only once, to determine the observed phenomenon):

- Step1: choose an observable,
- Step2: find one or more stimuli that are causally linked to the observable,
- Step3 (also called 'impression'): detect the stimuli producing analog signals, and
- Step4 (also called 'expression'): convert the analog signals to observation values.

The entity which produces the analog signal out the stimulus (Step 3) is termed the **receptor**. **Receptors** as defined here, are similar to the threshold devices introduced in (BRAITENBERG 1984), in that the production of the output (analog signal) doesn't happen immediately upon activation of the input (stimulus), but only after a short delay. However (and contrary to QUINE 1993), receptors are not considered as the interface between the external world and the observer. Said another way, receptors *don't need to be located at the surface* of the observer. The **spatial receptive field** (SRF) is the spatial region[6] of the observer which is *stimulated during the observation process*. The **temporal receptive window** (TRW) is the smallest interval of time required by the receptors in order to produce analog signals. The definition of SRF is compatible with the one of receptive field in Neuroscience as a "specific region of sensory space in which an appropriate stimulus can drive an electrical response in a sensory neuron" (ALONSO & CHEN 2009). The definition of TRW paraphrases and generalizes to all sensor devices, the one proposed in (HASSON et al. 2008; LERNER et al. 2011). The **spatial resolution** of an observation can be approximated by the **spatial receptive field** of the observer, and its **temporal resolution** could be equated with the **temporal receptive window** of the observer participating in the observation process. It should be noted that there might be many receptors in an observation process. The analog signal produced after the 'impression' can indeed be used as stimulus during the 'expression', and further processed by some receptors of the observer. In such cases, the relevant receptors for the computation of the spatial resolution are the ones that are stimulated by *external stimuli*. Figure 1 illustrates this point.

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6 This spatial region can be seen as two- or three-dimensional.

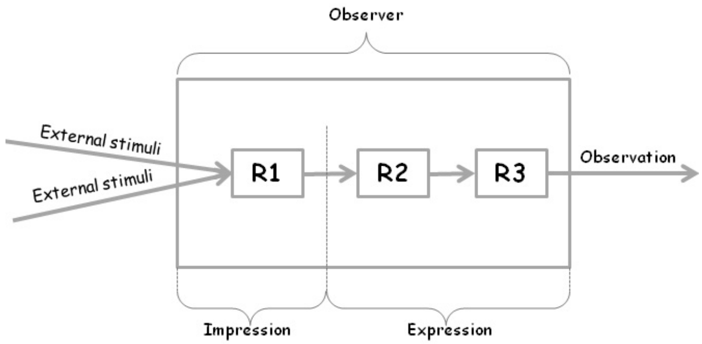

Fig. 1: Observer with several receptors: only receptor R1 is relevant to the estimation of the spatial resolution because it is directly stimulated by external stimuli

3.3 Discussion

Both the property-centric and the receptor-centric views are two equally valid ways of modeling the spatial and temporal resolution of one observation. In the first case, resolution is equated with the area, volume or time interval over which the property of interest is considered homogeneous (and hence the name 'property-centric'). In the second case, receptors are the center of attention. The spatial region containing all the receptors stimulated determines the spatial resolution, and the short delay required to produce the output (upon activation of the input) specifies the temporal resolution. The property-centric view has the advantage of familiarity (the term 'support' is well known to the domain of GIScience). The receptor-centric view, on the contrary, has the advantage that it is particularly convenient to account for the resolution observations produced by humans (as Section 3.4 illustrates). A happy medium is a receptor-centric definition of spatial and temporal support. That is: the **spatial support** is the spatial region of the observer which is stimulated during the observation process; the **temporal support** is the smallest interval of time required by the observer in order to produce analog signals. The temporal support is always greater than the temporal receptive window[7]. The three terms (spatial support, temporal support, and receptor) as defined in this section are adopted for the rest of the discussion.

3.4 Examples of spatial and temporal support for a single observation

A Carbon Monoxide Analyzer of type GM901[8] returns the concentration of carbon monoxide (Observation), with a **spatial support** equal to the size of the aperture, and a **temporal support** equal to the response time. The **spatial support** varies between 300 and 500 millimeters, and the value of the **temporal support** lies between 5 and 300 seconds. The **receptor** of the Carbon Monoxide Analyzer of type GM901 is the *measuring probe*.

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7 The temporal support is obtained by summing up the time needed for the 'impression' (= TRW), and the time needed for the 'expression' (Step 4 of the observation process outlined previously).

8 See http://www.sick.com/us1/en-us/home/products/product_portfolio/analyzers_systems/Pages/gm901.aspx; last accessed: March 27, 2013.

The temporal support of observations produced by human observers depends on the observer, the type of task, and the stimulus. For observations sentences[9] as defined in (QUINE 1993; QUINE 1995), the **temporal support** is in the order of a *fraction of second* for a word (e.g. 'beautiful' after the observation of a landscape), and in the order of few seconds for a sentence (e.g. 'it's delicious'). These values for the temporal support are assigned based on an earlier comment from (HASSON et al. 2008), namely: "it typically takes a fraction of a second to utter a word and a few seconds to utter a sentence".

The **spatial support** of human observations is equal to the size of the surface stimulated during the observation process. This surface might be calculated using the product N * S, where N is the number of receptors which have *participated* in the observation process, and S is the size of one receptor. As starting point for the computation, the knowledge presented in Table 1 can be used. The table is provisional, because the *exact* knowledge of the receptors which have participated in an observation process will become available as Neuroscience evolves[10]. Relevant references to the information presented in this table include (CHUDLER 2013, SOCIETY FOR NEUROSCIENCE 2012, OPTIPEDIA 2013, JENKINS et al. 2009, LEDERMAN 1997, MEYERHOF 2008, BRITANNICA.COM 2013a, BRITANNICA.COM 2013b, PINES 2013).

Table 1: Examples of receptors for a human observer

Sense	Receptors, number and size
Hearing	*eardrum* (or tympanic membrane) of the ear[11]; there is 1 eardrum per ear; the surface area of an eardrum is about 85 mm^2
Sight	*photoreceptors* of the retina; photoreceptors are about 125 million in each human eye; their diameter varies roughly between 2.5µm and 10µm
Smell	*olfactory cilia* of the olfactory neuron in the nose; there are about 5 million olfactory neurons in each nose, each neuron has 8-20 cilia; cilia have a length between 30 and 200µm
Taste	*taste buds* of the tongue; a human has between 5,000 and 10,000 taste buds; taste stimuli interact with taste buds at a small 2-10µm region called the taste pore
Touch	*touch receptors* of the skin; there are about 17,000 touch receptors in the human hand; the mean spatial receptive field of touch receptors of type FAI is about 12.6 mm^2

As this section demonstrates, a receptor-centric definition of spatial and temporal support is applicable to both in-situ (e.g. tongue) and remote (e.g. the human eye) sensors, and to both human and technical observers (the carbon monoxide analyzer). Section 4 presents the

9 Observation sentences refers to a word (or group of words) assigned unreflectively, on the spot to external stimuli.

10 KRULWICH (2007) indicate that it is only in 2002, that it became the new view that there is a fifth taste (umami), in addition to the four admitted during many centuries (bitter, salty, sour, sweet). This fifth taste is detected by a specific type of receptors (receptors for L-glutamate on the tongue).

11 Treating eardrums as receptors (instead of the hair cells of the cochlea for example) is the direct consequence of the fact that receptors in this context *must be* directly stimulated by external stimuli.

formal specification of the ontology in Haskell as well as the alignment of the terms observer, resolution, and receptor to DOLCE.

4 Formal Specification of the Resolution of a Sensor Observation

The case of a human observer hearing a sound and producing an observation value is taken as running example for the formal specification. The stimulus is a sound wave which has an id and an amplitude, that is:

```
type Id = Int
data SoundWave = SoundWave {stimulusId : : Id, amplitude : : Double}
soundwave = SoundWave {stimulusId = 1, amplitude = 73.0  }
```

A receptor has an id, a size and a temporal receptive window. For the eardrum, the size is 85 mm^2 (see Table 1) and the temporal receptive window is set provisionally to 0.5 seconds.

```
data Receptor = Receptor { receptorId : : Id, size : : Double, trw : : Double }
eardrum = Receptor { receptorId = 1, size  = 85.0, trw = 0.5 }
```

An observer has an id, a limited number of receptors, a temporal support, a quale, an observation value, and has its receptors activated or not. For simplicity, it is assumed here that all the receptors are alike, and there is no malfunction during the observation process (i.e. either all the receptors are triggered or none of them is triggered). A human observer has 2 eardrums.

```
data Observer = Observer {observerId :: Id, numberOfReceptors : : Double,
temporalSupport : : Double, receptorType : : Receptor, quale : : Double,
receptorTriggered : : Bool, observationValue : : String }
humanObserver = Observer {observerId = 1, numberOfReceptors = 2,
temporalSupport = 0.0, receptorType = eardrum, quale = 0.0,
receptorTriggered = False, observationValue = " " }
```

Below is the alignment of the term 'observer', and 'receptor' to DOLCE as well as the definition of resolution as belonging to the DOLCE's class abstract quality.

```
-- an observer is an agentive physical object
instance PHYSICAL_ENDURANTS Observer
instance PHYSICAL_OBJECTS Observer
instance AGENTS Observer

-- a receptor is an agentive physical object
instance PHYSICAL_ENDURANTS Receptor
instance PHYSICAL_OBJECTS Receptor
instance AGENTS Receptor

-- resolution as an abstract quality
class ABSTRACT_QUALITY stimulus observer => RESOLUTION stimulus observer where
perceive :: stimulus -> observer -> observer
observe :: stimulus -> observer -> observer
spatialResolution :: stimulus -> observer -> Double
temporalResolution :: stimulus -> observer -> Double
```

During the perception of the stimulus, the receptors of the observer are triggered, the quale of the observer takes the value of the amplitude of the stimulus, and the temporal support is initialized to the temporal receptive window of the receptors.

```
instance RESOLUTION SoundWave Observer where
perceive stimulus observer = observer { receptorTriggered = True, quale = amplitude
stimulus, temporalSupport = trw (receptorType observer )}
```

Based on the quale, the observer produces an observation value, and the smallest interval of time needed to produce this observation value is added to the temporal receptive window of the receptors. In the example below, the observer produces the value “a bit loud” if the sound is greater than 70 decibels, and it is assumed that 0.2 seconds are needed for this operation.

```
observe stimulus observer = observer {quale = quale (perceive stimulus observer),
observationValue = if (quale (perceive stimulus observer )) > 70 then "a bit loud" else "the
sound is appropriate", temporalSupport = temporalSupport (perceive stimulus observer) +
0.2, receptorTriggered = receptorTriggered ( perceive stimulus observer)}
```

The spatial resolution of the observation is the spatial support of the observer, and the temporal resolution of the observation is the temporal support of the observer. The spatial support can be estimated using information about the perception operation, but information about the duration of the whole observation process is required to estimate the temporal support.

```
spatialResolution stimulus observer = spatialSupport (perceive stimulus observer)
temporalResolution stimulus observer = temporalSupport (observe stimulus observer)
```

The last stage of this formal specification is the definition of the spatial support as the size of all receptors triggered during the observation process. Spatial support is undefined when no receptor has been triggered during the observation process.

```
spatialSupport :: Observer -> Double
spatialSupport observer = if (receptorTriggered observer == True )
then (numberOfReceptors observer ) * size ( receptorType observer )
else undefined
```

The Haskell code for the specification can be obtained upon request to the author, or retrieved from http://ifgi.uni-muenster.de/~degbelo/Resources/ObservationResolution.hs.

5 Conclusion and Outlook

Resolution is an unavoidable limitation of geographic datasets, and there is currently no theory of resolution for observations underlying geographic information. This paper is a first step towards the provision of such a theory, with a focus on spatial and temporal resolution of a single sensor observation. It has been suggested to model spatial resolution of an observation as being equal to the spatial support of the observer, and temporal resolution as being the temporal support of the observer. Spatial support and temporal support have slightly been redefined as “the spatial region of the observer which is stimulated during the observation process”, and “the smallest interval of time required by the observer in order to produce analog signals” respectively. Different examples were provided to demonstrate the applicability of such definitions to both in-situ, and remote sensors, technical and human observers. A formal specification in Haskell (with a running example of a human observer hearing a sound and producing an observation value) was used to test the consistency of the fragment of theory proposed.

Directions for further work include a formal specification of the resolution of an observation collection (i.e. many observations about the same phenomenon), and the implementation of the theory using ontology encoding languages. Ontology design patterns as introduced in (GANGEMI 2005, GANGEMI & PRESUTTI 2009) may prove useful in that context because they are halfway between ontology design which was the focus of this paper, and ontology implementation.

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