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Haphazard occurrences of reality: the link between opportunism, geodesy, and satellite radar interferometry

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Hendrik Casimir, the renowned Dutch physicist, quoted in his autobiography the aphorism: "When telling a true story one should not be over-influenced by the haphazard occurrences of reality." He implied that as long as the main message (the true story) of an anecdote is correct, the anecdote may be worth telling, even if it has no factual basis. Although I do not intend to dwell on anecdotes in this brief retrospective, I was struck by the implications of the aphorism to my studies on the geodetic applications of satellite radar interferometry.

The haphazard occurrences of reality reflect a concept well known in contemporary geodesy: repeatedly measuring a physical parameter (reality) will result in stochastically dispersed numerical observations. In this context, the haphazard occurrences of reality are in fact a nuisance, one would rather know the true story instead of having to interpret dispersed observations. Nevertheless, geodetic science has learned to live with this concept, for example by introducing redundant observations and network optimization to determine not only the parameter of interest, but its higher-order stochastic moments as well. Concepts such as reliability enable quantitative statements on the tuning between the functional and the stochastic models. Many types of geodetic surveying techniques, from terrestrial triangulation to the global satellite navigation systems, are built on these concepts. All of these techniques have in common that they are based on some kind of prior knowledge. For example, for monitoring a deformation signal its existence should be anticipated, but also its type, size, and properties. Rarely observations are performed without any a priori ideas on the parameter of interest.

Satellite radar interferometry (interferometric synthetic aperture radar, InSAR) is one of the techniques where this paradigm cannot be applied straightforwardly. For example, since the complex radar observable is formed by the many reflections of a radar wave on the earth's surface –a deterministic process but usually impossible to model - we actually do not know what we are measuring. Distilling the desired geometric information from this observable is a non-trivial task. Redundant observations are usually not available, leading to poor-mans' redundancy, based on harsh assumptions of ergodicity. Due to the fixed orbital schedule of the radar satellites, optimization of the survey strategy for, e.g., deformation monitoring is limited only to a few experimental situations. On the other hand, one could argue that since the millions of observations in each radar image are routinely available, and that every position on earth can nowadays be observed with a revisit time of days, the application of the technique deserves a sound geodetic foundation. In fact, the challenge is to find the true stories from the haphazard occurrences of reality. Identification (and, later, interpretation) of observations that are physically meaningful is the key issue here. Applied to deformation measurements, it can be a tool not only for observing anticipated deformation signals, but also allows for the detection of new, unexpected phenomena.

Radar interferometry can be used for observing topography, surface deformation, and integrated atmospheric refractivity, depending on the interferometric configuration [1,5,8,10]. Topographic mapping has been successfully applied in e.g. the topography mission of the Space Shuttle, leading to the first consistent and uniform elevation model of the world between +/- 60 degrees latitude [11]. Currently, several proposals for InSAR satellite missions for elevation mapping are under serious consideration. Atmospheric mapping can be regarded as a side-topic for most geodetic applications, but the concept of measuring the fine-resolution water vapor distribution using interferometric imaging radar has revealed unprecedented views of meso-scale atmospheric phenomena, sparking new ideas in meteorology and improved stochastic models in space-geodesy [4,6,7]. Nevertheless, the most spectacular scientific advances have been made in the field of deformation monitoring, considering geodesy as well as geophysics [5].

Geodetic deformation monitoring using radar interferometry was boosted when the first interferograms of the coseismic displacement field due to earthquakes were published on the cover of Nature [9]. These semi-continuous images were among the first realizations of an 'opportunistic' technique - exploiting the opportunity of combining an archived radar image with a newly acquired one. Since the satellite ERS-1 was not designed for interferometry, these 'by-products' were indeed a major achievement, although they created lofty expectations as well.

The expectations based on the successes with earthquakes, glacier and volcano dynamics, and subsidence created a belief that any problem of deformation could now be monitored from space, routinely, with minimal costs, and maximum accuracy. While proceeding to deformations with smaller displacements, in more humid environments, and over longer time periods, it did not take long to acknowledge the opportunism in the InSAR successes. Under these more unfavorable conditions, radar interferograms reduced from the cheerful color-fringes to explosions of pure and uninterpretable noise. Moreover, elevation products started showing artificial mountain chains, an effect of unaccounted atmosphere. The stories were truly obscured by the haphazard occurrences of reality.

The problems encountered set the stage for new approaches and improved algorithms. The problem of the atmospheric signal, embedded in the phase observations, is challenged by using a multitude of radar acquisitions, exploiting the lack of correlation of the signal between subsequent acquisitions. More important, a systematic approach for discerning coherent radar reflections from incoherent ones reveals only those observations that are physically interpretable [2,3]. Single pixels in the radar image, even fractions of pixels, can now be interpreted in terms of their deformation, elevation, and atmospheric error. Formal precisions for these parameters could be in the range of sub-mm/y for (linear) deformation and sub-meter for elevation [3]. Solving these parameters is possible only if tens of radar acquisitions are available for analysis.

Even though these possibilities are beyond imagination considering satellites at 800 km altitude, the observations are still opportunistic. Although the measurements may show the displacement of an object with a precision better than one millimeter per year, there is no guarantee that a similar result may be obtained for another object in the radar image. Whether a target is coherent depends on the combination of its physical and geometric characteristics with the specific point of view and characteristics of the radar sensor. Two topologically identical objects with a different orientation may behave completely different in the radar image. The adage is therefore, again, opportunism---results cannot be predicted until the data are processed and interpreted. On the other hand, it is important to realize that (i) in many cases the radar data are the only data available, (ii) experience in many case studies showed that often good results can be anticipated, especially in an urban environment, (iii) the temporal update frequency is much higher compared to many conventional techniques, (iv) archives of radar data allow for an a posteriori analysis of areas of interest, and (v) future plans for SAR satellites indicate an increasing amount of data to be available.

In the evolution of methodology and algorithms for interferometric radar many hurdles have been taken. Nevertheless, there are still many open questions where geodesy can play a leading role. For example, the stochastic model of the radar observations needs to be better defined, integer ambiguities in the phase observations (both spatially as well as temporally) need to be solved, and the observations of the different radar satellites and additional geodetic techniques need to be integrated systematically to estimate the parameters of interest. Many numerical problems related to the number and size of the data sets need to be resolved. Additionally, the observation of very local geophysical or geotechnical deformation phenomena requires a close collaboration with disciplines such as hydrology, geophysics, geology, and civil engineering.

In conclusion, I hope that the advent of 'opportunistic' techniques such as radar interferometry and their related problems and challenges has demonstrated their complementary value in the field of geodesy. Although we have to deal with the 'haphazard occurrences of reality', there are many great stories to be told.

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References

Richard Bamler and Philipp Hartl. Synthetic aperture radar interferometry.
Inverse Problems, 14:R1--R54, 1998.

Alessandro Ferretti, Claudio Prati, and Fabio Rocca. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry.
IEEE Transactions on Geoscience and Remote Sensing, 38(5):2202--2212, September 2000.

Alessandro Ferretti, Claudio Prati, and Fabio Rocca. Permanent scatterers in SAR interferometry.
IEEE Transactions on Geoscience and Remote Sensing, 39(1):8-- 20, January 2001.

Ramon Hanssen, Ilona Weinreich, Susanne Lehner, and Ad Stoffelen. Tropospheric wind and humidity derived from spaceborne radar intensity and phase observations.
Geophysical Research Letters, 27(12):1699--1702, June-15 2000.

Ramon F Hanssen. Radar Interferometry: Data Interpretation and Error Analysis.
Kluwer Academic Publishers, Dordrecht, 2001.

Ramon F Hanssen, Arnout J Feijt, and Roland Klees. Comparison of precipitable water vapor observations by spaceborne radar interferometry and Meteosat 6.7-m radiometry.
Journal of Atmospheric and Oceanic Technology, 18(5):756--764, May 2001.

Ramon F Hanssen, Tammy M Weckwerth, Howard A Zebker, and Roland Klees. High-resolution water vapor mapping from interferometric radar measurements.
Science, 283:1295--1297, February-26 1999.

Didier Massonnet and Kurt L Feigl. Radar interferometry and its application to changes in the Earth's surface. Reviews of Geophysics, 36(4):441--500, November 1998.

Didier Massonnet, Marc Rossi, Cesar Carmona, Frederic Adagna, Gilles Peltzer, Kurt Feigl, and Thierry Rabaute. The displacement field of the Landers earthquake mapped by radar interferometry.
Nature, 364(8):138--142, July-8 1993.

Paul Rosen, Scott Hensley, Ian R Joughin, Fuk K Li, Soren Madsen, Ernesto Rodriguez, and Richard Goldstein. Synthetic aperture radar interferometry.
Proceedings of the IEEE, 88(3):333--382, March 2000.

S Suchandt, H Breit, N Adam, M Eineder, B Schattler, H Runge, A Roth, and E Mikusch. The shuttle radar topography mission. In ISPRS Workshop, High Resolution Mapping from Space, Hannover, Germany, 19--21 September 2002, pages 235--242. ISPRS, September 2001.