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THE DETECTION OF CRUSTAL MOVEMENTS BY GEODETIC SPACE TECHNIQUES

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THE DEFORMING EARTH

The earth surface is continuously deforming! The most conspicuous causes of these deformations, arranged from the best understood (the most accurately predictable) to the least understood (the least accurately predictable) are as follows:

1) **Tides** -
body tides: the "breathing of the earth" cause global deformations in the one metre range;
sea tides: sea covers over 72% of the earth surface, hence sea surface deformations should be considered alongside the solid earth deformations; the largest range is 16.3 metres;
sea-tide loading: small, in the centimetre range.

2) **Crustal loading** -
ice: the weight of existing Antarctic ice is estimated at 2.7×10^{19} kg; the Laurentide region was depressed during the last glaciation by about 500 m;
ice melt (water): after the last ice age, an estimated 3×10^{19} kg of water was released from the melted ice; consequently, sea had risen by about 80 m and sea bottom subsided by metres under the load of this water;
river deposits: the Mississippi river deposits up to 8×10^{11} kg of silt annually close to its estuary; this is an example of an evolution of a sedimentary basin, where accumulated subsidence can be measured in tens of metres;
tidal water: (see above);
man made loads (reservoirs, cities, etc.): lake Kariba weighs about 1.5×10^{14} kg; weight causes subsidence in decimetres;
and unloading -
ice melting: the Laurentide region rebounded by 350 metres and is still rising by up to one centimetre per year;
evaporation of lakes: Great Salt Lake lost some 8.2×10^{15} kg of water and consequently rebounded by up to 7 metres;
erosion: comparable with evaporation, no reliable data are available.

3) **Tectonic deformations -**

spreading boundaries: average rate 2 centimetres per year, rifting much faster, up to 15 cm/year; volcanic activity, earthquakes;
converging boundaries: trench evolution, orogeny, the most destructive earthquakes; volcanic activity;
intra-plate phenomena: geosyncline, faulting, graben and escarpment evolution; earthquakes.

4) **Man-made and other -**

ground compaction: is caused by fluid withdrawal and is of local or regional character; many metres of subsidence have been observed;
caving in: is caused by underground mining and by a collapse of natural cavities; subsidence by several metres has been observed;
landslides: a self-evident change of the earth surface shape;
sea-level variations: eustatic rise (2 mm/year), waves, tides (see above), tsunami, seiches, wind-driven pile-ups, etc.

THE PROBLEM OF PREDICTION

Many of the above mentioned deformations are inconsequential for everyday human activities. Take for instance the body tide which is too global for us to sense it, or the evolution of escarpments or sedimentary basins which is too gradual for us to worry about it, or sea-tide loading which is too small to affect us in any way. These phenomena we do not have to even know about. Or, we may be living far away from where some of these things are happening. When we live in Japan, we do not have to worry about post-glacial rebound, or the lake evaporation rebound. When we live in eastern North America, we do not have to worry about volcanic eruptions.

Some of these deformations, such as sizable earthquakes, tsunami, or volcanic eruptions, affect many people very directly in different parts of the world, often with disastrous consequences. It is these phenomena, that we would like to be able to predict, to minimize the potential death toll and damage.

How do we go about predicting the phenomena of interest? As in any other field, prediction is done by models. These models are nothing but mathematical equations that describe the behaviour of the earth in time. To put together these equations, i.e., the model, we have to first understand the physics of the phenomenon, i.e., the forces that cause the deformation and the way the earth responds to these forces. This understanding comes only from studying the ongoing processes. And this is where geodesy comes on the scene.

THE ROLE OF GEODESY

What is geodesy? Geodesy is the science that concerns itself with the geometry of the earth, the earth's gravity field and their temporal variations. Clearly, the evolution of the geometry of surface deformations, or crustal motions, as we often refer to them as, is of a paramount interest to geodesy. However, the focus of professional attention for a geodesist is not the design of a realistic model for a deformation phenomenon; rather, it is the impact of the crustal motion on positions (coordinates) of geodetic control points. Positions of points at the earth surface are needed whenever one deals with spatial arrangement of objects, from the traditional maps to computerised geographical information systems.

Whatever their interest may be, the fact is, that geodesists are the people best equipped to measure and calculate repeatedly the most accurate positions of points on the earth surface. Such repeated positions that geodesists determine, can then be used to describe the evolution of earth's surface deformation geometry. When a more spatially detailed description is needed, more densely distributed points have to be repeatedly surveyed. When a more refined picture of the evolution in time is desired, the time intervals between repeated surveys have to be shortened.

In the past, the positions of geodetic points on the earth surface were determined in an incremental fashion from terrestrial measurements of angles, distances, height differences, astronomical azimuths, astronomical latitudes and longitudes. With the advent of artificial satellites and radio-astronomy, and their progress in the past 30 years, geodesists now have new and generally more accurate tools for positioning. With these new 'space tools', it is now possible to determine accurately even positions of isolated points, as well as accurate relative positions of points located from a few metres to many thousands of kilometres apart.

To study local and regional crustal motions, the classical terrestrial positioning techniques can be and still are used. For studying the global crustal motions, when changes in positions of points located very far apart are needed, space techniques must be used. Some space techniques, however, are used even to position points in the regional, or even local context.

GEODETIC SPACE TECHNIQUES

What are these space techniques all about? They are all based on the idea of taking measurements to some extra-terrestrial objects. The best results, i.e., the most accurate positions or position differences, are obtained by using either the closest available objects, artificial satellites, or the most distant objects, quasars (quasi -stellar radio sources). For determining global crustal motions to a sufficiently high accuracy, we thus use, on the one hand, satellite positioning techniques and, on the other hand, radio-astronomy. Other existing space techniques do not have the required accuracy to be really useful in crustal motion applications.

The measurements to these space objects are, in the ascending order of positioning accuracy: directions, distances and distance differences. Again, for meaningful global crustal motion determination, only distances and distance differences can be measured accurately enough. These are measured by means of precise timing of the propagation of electromagnetic waves of very high frequencies.

In addition to the measurements, the positions of the satellites, or quasars vis-a-vis the earth at the instants of measurements, must be known as accurately as possible. Since quasars are believed to be millions to billions of light years away from the earth, their distances from the earth are considered practically infinite and only directions to quasars measured from the earth are required.

The three most popular positioning systems which are accurate enough, and thus usable for global crustal motion monitoring, are: the Satellite Laser Ranging (SLR), Global Positioning System (GPS) and Very Long Baseline Interferometry (VLBI). These systems may be briefly characterised as follows:

1) **SLR** - is a loosely organised and very accurate system consisting of dedicated satellites and some permanent as well as mobile tracking stations. At present, there are 6 dedicated "laser satellites" (LAGEOS I & II, AJISAI, STARLETTE, ETALON I & II) available for ranging. These satellites are completely passive, in a shape of dense balls of up to one metre in diameter, covered with retro-reflectors. They are in orbits of inclinations ranging between 50 and 110 degrees, at altitudes ranging between 810 and 19,100 km. Because of their simple spherical shape, their orbits, i.e., strings of positions in space, can be computed very accurately, more accurately than orbits of any other satellites.

The ground stations designated to track these satellites with lasers, must be equipped with good astronomical telescopes designed for fast tracking, and with high quality clocks. The laser must be powerful enough to emit light pulses capable of traveling for several thousands of kilometres and passing through the whole thickness of atmosphere back and forth. The total travel time of the laser pulse from the transmitting telescope to the satellite retro-reflector and back to the receiving telescope is timed precisely. This time interval is then converted to distance. The position of the laser is then computed from these distances and the post-fitted orbits of the tracked satellites, at some later date. The errors in so determined positions are of the order of one centimetre.

2) **GPS** - is an all weather system consisting of 24 identical satellites orbiting the earth at an altitude of about 20,000 km, revolving around the earth twice a day, at an inclination of 55 degrees, and a set of ground control stations. Each satellite continuously transmits its own particular signal at two frequencies of about 1200 and 1500 MHz. The signals of all the satellites are precisely synchronised and the frequencies kept as constant as possible by 3 very accurate atomic and one crystal clocks that operate (not simultaneously though) on board of each satellite. Each satellite also continuously transmits information about its own position in space.

Signals from the satellites "visible" to the observer are received by the antenna of the receiver, the instrument with which we make the measurements. These instruments, commercially available, relatively cheap and in geodetic applications employed always in pairs, then measure very accurately the continuous changes of ranges to all the simultaneously tracked satellites. This is done by means of another precise clock built into each receiver. From these changes, and from the received satellite positions, receivers can determine very accurate spatial differences in the positions of their respective antennas, i.e., the spatial "baselines" between the two antennas. These baselines may be of an arbitrary length and orientation and can be readily determined to an accuracy of a few parts in 10^{-7} (a few decimetres in 1,000 kilometres) and even better with a sophisticated analysis.

3) **VLBI** - is a radio-astronomical technique designed to measure very long baselines, typically several thousands of kilometres long. It uses quasars as sources of the signal tracked by the receivers. Quasars transmit signals that contain a broad band of frequencies; from these only narrow bands around 2 and 8 GHz are actually used for tracking. Quasars are so far away that the directions to them appear stationary in space.

Since the signals coming from quasars are very faint, very large radio-telescopes and powerful amplifiers are needed to track them. These radio-telescopes, called "dishes'" in the technical slang, are employed in pairs, simultaneously to track quasar signals, one at a time. The selected bands of the signal, corresponding to the wavelengths of a few centimetres, are then recorded on tapes, together with very precise time marks issued periodically by the observatories' dedicated hydrogen masers, the most stable atomic oscillators available. After each observing session, lasting normally for one to a few days, the recordings are brought together and processed in a "correlator", a device that converts the recorded signals into range differences. From these continuously varying range differences and the known directions to quasars, very accurate baselines can be computed. The errors in so derived baselines may be as small as a few centimetres.

There exist other spatial systems that can and are used for global crustal motion monitoring, such as for example the French DORIS system, but these are less popular and we shall not describe them here.

EXAMPLES OF SOME ONGOING PROJECTS

The best known and the longest running (since 1979) global project is the **Crustal Dynamics Project**, renamed in 1992 to **Dynamics of the Solid Earth** (DOSE)**,** conceived and managed by NASA. Under the auspices of this project, NASA and scores of its external collaborators periodically employ many of the world's radio-telescopes and lasers to survey and re-survey positions of strategically selected points all around the world. From so determined position changes, the pattern of motion of tectonic plates can be discerned. The results obtained from about 15 years of observations seem to confirm, to a good accuracy of a few centimetres per year, the estimated plate velocities derived from other evidence.

The recently (1991) established **International GPS Geodynamics Service**, a cooperative venture of some 150 different institutions around the world under the auspices of the International Association of Geodesy, continuously determines positions of some 120 stations and operates 6 centres, which independently produce very accurate post-fitted orbits for all GPS satellites. It become fully operational at the beginning of 1994 and started providing not only the information on position changes of its 120 permanent (fiducial) stations but also precise GPS orbits for independent researchers who wish to use the GPS for crustal motion monitoring.

Many regional crustal motion projects have been and are being conducted. Most of these projects employ the GPS as their basic tool, because it is the cheapest and the easiest to use. The longest running of these projects is probably the cooperative project in California, which monitors the ongoing deformations along the Saint Andreas system of tectonic faults.

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