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VOLCANO DEFORMATIONS

OPTIMIZATION OF AVAILABLE METHODOLOGIES

DIREKTORAT VULKANOLOGI

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INTRODUCTION

This article is an overview of the various methodologies that one may use to monitor ground deformations, especially on active volcanoes. These methodologies are generally derived from well-established topographic techniques, about which we will suppose that the reader has already a good knowledge; would it not be the case, we suggest to the non-surveyors who are interested in this matter to begin by reading a classical textbook about geodetic and levelling methods. This paper aims to provide the reader with the only aspects which are specific of deformation surveys, with special attention paid to optimization processes of practical and technical aspects. That is to say, how to do the most appropriate measurements at a minimal cost. A lot of publications have already dealt with such topics, but quite often they present the point of view of scientific researchers. Here, one can find the point of view of an engineer, which is sometimes a bit different. I think that with the increasing interest that the scientific community has for ground deformations studies, it is due time for these disciplines to get into a new phase of optimization, as the technical ways to get a given information are becoming increasingly numerous, and even sometimes appear to the non-specialist as quite equivalent. So may these few pages help all the people technically involved in ground deformations to choose the most suitable solutions for each case.

The last preliminary remark to be done now concerns the important difference between "accuracy" and "precision" one has to be aware of. The precision characterizes the difference between the perfect ideal value and the actual one, but the accuracy is the resolution of the measuring system, its ability to display a difference between two readings. When a system is properly designed, its precision is not as good as its accuracy, and it is considered preferable that the accuracy should not limit the precision of a given measurement.

I.DETECTION OF VERTICAL MOVEMENTS

I.1.Introduction: General Problems.

Today a lot of ground deformations can be measured quite easily with methodologies derived from topography, geodesy and levelling. However, it quite interesting to notice that since the beginning of good precision levelling and geodesy (e.g. abbe Picard in XVIIth century), and even possibly before (despite a small number of well-documented examples, like a water gallery in Samos, Greece), the precision of vertical surveys has often been much better than horizontal survey's one. This is due mainly to the extreme facility one has to detect the position of the vertical (zenith or nadir) compared with the quasi-total lack of easy-to-find horizontal reference (like the North, for example). And up to now an important difference subsists between the ultimate precision of horizontal networks (1ppm, or 1mm/km) and of vertical ones (0.1 mm/km). Only with highly sophisticated methods is it possible now to reach the 0.1ppm level for horizontal surveys (two-wavelength EDM, some of the spatial geodetic methods). In fact, a rough analysis of the refraction processes should have led us to a quite different conclusion, as they affect the ray paths only in the vertical direction, so that it should strongly limit the efficiency of vertical surveys. The answer to this remark is that excellent field procedures have been used to limit or even cancel refraction effects (using short lines of sight for examples), and the limiting factors of these surveys are generally not due to the atmospheric travel of the light.

For these reasons, the first ways to detect ground movements have been the most precise ones, that is to say the vertical topographic methods. There are many technical possibilities that we can use today, all of them may be employed for volcano deformations where the expected movements are generally very small and rarely allow one to use rough methods in an useful way.

I.2.Resurveying of existing levelling networks.

Many countries in the world have a national high-precision levelling network which is of outstanding interest for every hydraulic constructions, like distribution of water and sewerage systems. Such a network is a costly feature (in France for example it costs 300 man months of field work every year) and generally it has a lifetime of 30 to 50 years, which means that complete new measurements are to be made within this time interval. The basic method is the direct or "spirit" levelling, providing a precision of say 1 to 2 mm/(square root of the distance in Km). Such existing networks may be sometimes of very high interest if one wants to know the behavior of a given area during the past years or tens of years. We have just to reobserve some of the levelling lines previously surveyed by the national office in charge of that network, and compare the new data with the old published altitudes, so that it looks very simple. Nevertheless many problems arise:

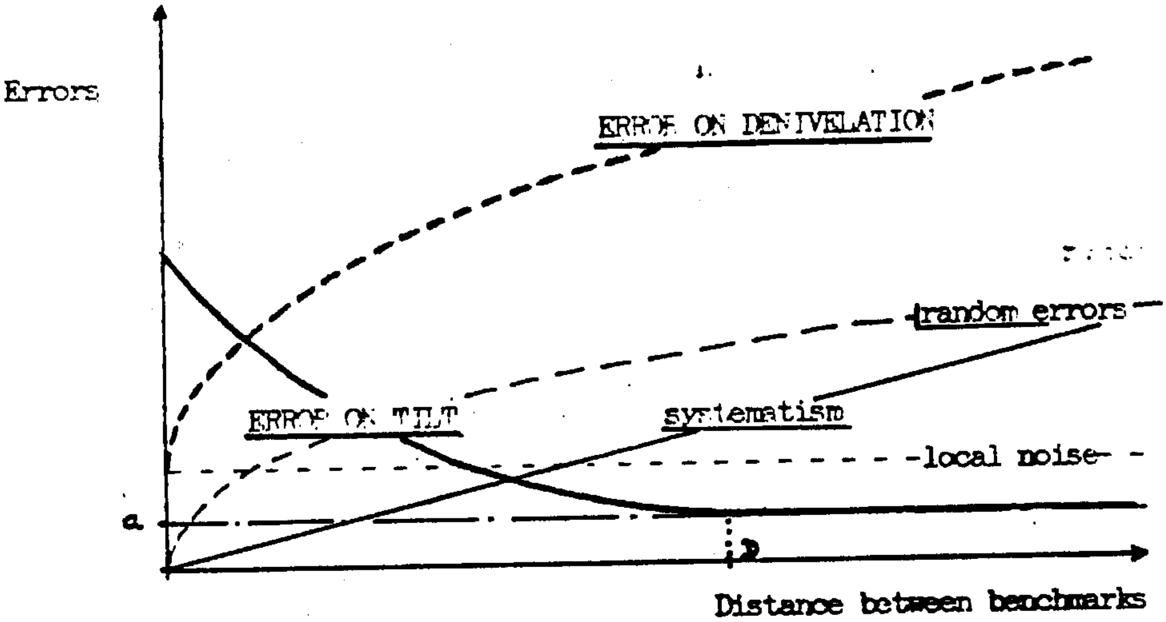
I.2.A.Reference

The only comparable physical data are the denivelations between the benchmarks (deduced from the differences of altitudes already published for the old data). And it exists absolutely no way to get an absolute reference for comparisons of levelling data. We have always to assume that a given point we choose is stable, or has a given vertical movement between the two epochs where measurements were performed. We depend from a model, and we have no good solution to get rid of it, so generally we can only use the results to monitor the tilt of the ground. And, every time we try to observe the complete vertical deformation pattern along a given profile, we must reobserve a line beginning on benchmarks far from the volcano if we want the assumption that they are "stable" is acceptable (with respect to this volcano).

I.2.B. Stability of the benchmarks

The benchmarks we can use have often been set up many years ago, on various types of supports (houses, aqueducts along the roads, walls, etc...). They have been located with special attention paid first to their ease of use for surveyors (ease to find them again after many years, if possible out of private properties, etc...). These various types of buildings may have moved with respect to the surrounding ground, and nearly always have actually moved. The only thing we can do is to try to qualify the support: the better it is, (big rock, old and strong building for example), the minimum his spurious movement will be. Thus we see that the movements we get from a comparison between levelling data have always to be carefully interpreted in order to eliminate possibly all phenomena devoid of interest. It seems that the only way to do that is quite empirical: we will assume that a given benchmark is stable and may be used as a reference when the denivelations between it and the neighboring benchmarks have not changed. This is not very easy to use as it may create confusions between useful and useless movements, and the true signal/noise ratio is rather uneasy to appreciate.

These considerations lead us to the following estimations for the precision: We must combine the errors of measurement of the two sets of data (proportional to the square root of the distance between the benchmarks) with a local error, mainly proportional to the time elapsed since the initial measurements and due to the instability of the benchmark (which in most cases obviously increases with time). So we shall consider in rough terms that the significance of a comparison of denivelations measured between two benchmarks at two different epochs is a function of the distance between these benchmarks according to the following drawing:



The error on denivelation is the resulting of random (proportional to the square root of the distance) and systematic errors, mixed with the local noise

a = long distance error on tilt

D = Distance beyond which the errors are mainly due to systematisms

I.2.C. Reliability of old data

It is sometimes quite difficult to analyze the quality of the old observations, as it is uneasy to know the instruments used, the field methodology, the skillfulness and care of the observers, and so on. The classical way to present the errors in high precision levelling involves random errors with a Gaussian distribution (a noise) on which are superimposed small systematic errors, generally extremely difficult to mitigate and whose effects are the combination of a lot of causes (sun on the tripod, refraction, shade on the rod, vertical movements of the instruments during observations,etc.).

In order to check the quality of the observations, the total denivelation along a closed loop is computed (theoretically it should be zero after the geopotential corrections have been made), and this "misclosure" is distributed along the loop so that after this operation it seems nullified. The main problem is that such a way to process data is able to remove only a certain type of systematisms, namely the ones linked to the direction of progression of the team along the line surveyed. The estimation of the possible other systematisms has been for ages the main unsolved problem of high precision levellings. Then a new consequence is that an apparent regional tilt of the ground may be an artefact, and its level of significance depends from its value: Strong tilts are nearly always true, but small ones must be considered with great care, as they may be just the expression of differences of systematisms between the two operations.

So in a few words, in order to summarize:

* The only information we often get concerns the tilt only.

* Movements of "small" spatial amplitudes may be spurious effects of local instabilities of old benchmarks.

* Movements of "small" amplitude on "large" zones may be spurious effects of hidden systematisms.

* The task of the geophysicists is then to get a good and adequate evaluation of these words "small" and "large".

A lot of movements without any geophysical significance have been already presented sometimes as interesting tectonic or volcanic behaviors: It is very important to keep these remarks in mind for an efficient analysis. These data on another hand must not be underestimated as they represent an enormous amount of information when properly used, and they are extremely cheap in some cases. For example, when the whole network is resurveyed for technical reasons (e.g. obsolescence, if a large proportion of benchmarks has been destroyed) it is just a matter of doing a few substractions. For each subsisting old benchmark we just have to compare the denivelations obtained for successive epochs, which is very simple...

I.3.Classical high precision levelling

When no existing levelling network is available, high precision levelling proves to be always a very good way to monitor ground tilt, and in some way the same remarks we have previously done are still valid.

However, if no benchmarks already exist, we would design them in a quite different manner from what is done for a national network:

* We must design stable benchmarks, without taking care for the cost of settlement, as it will concern only a few tens of units (instead of hundreds of thousands for a national network). A good way is to design them as for the dry-tilt stations (viz. paragraph IV.2).

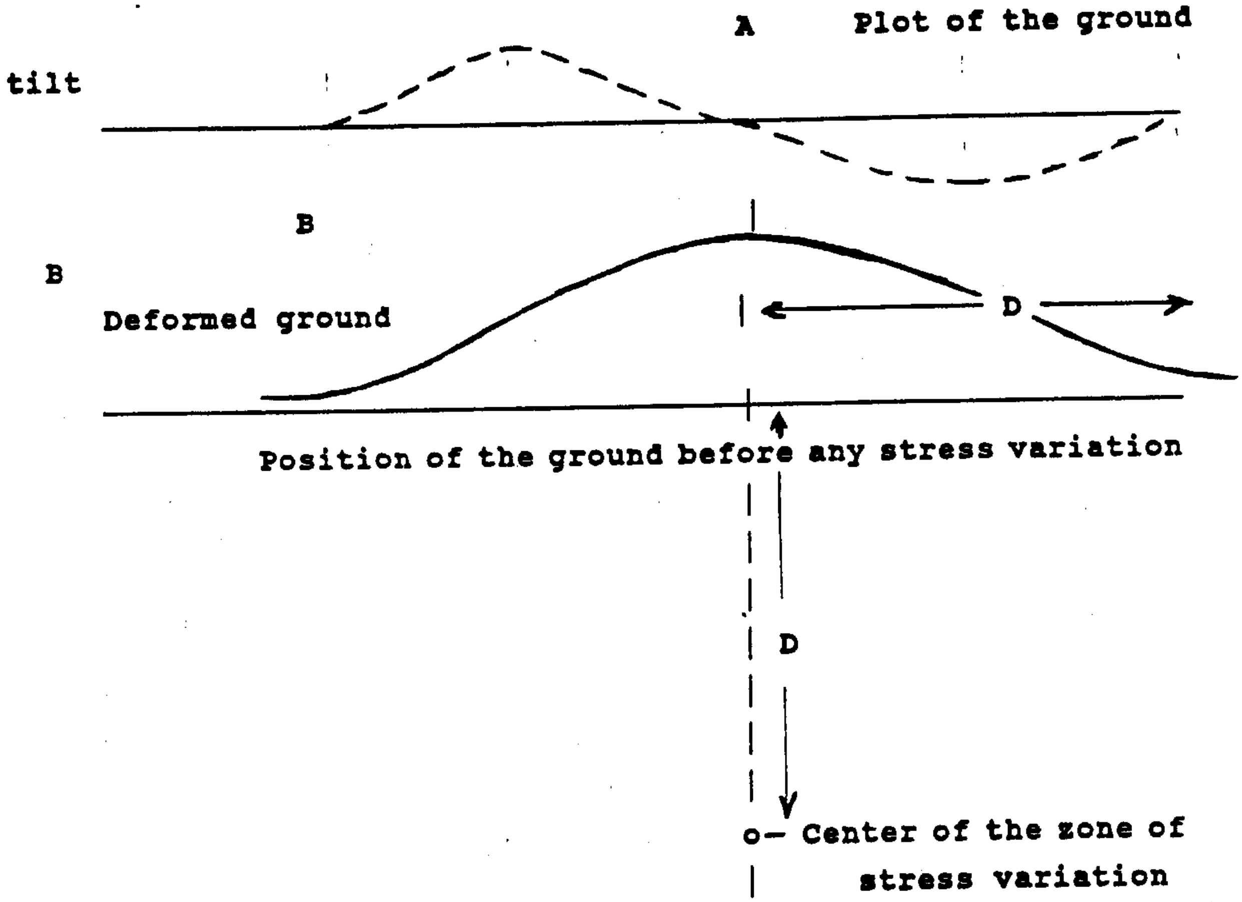
* The benchmarks may quite conveniently be hidden underground in order to avoid any shock (voluntary or not). They

will be more difficult to find again, but this is not a problem when a good description of the surrounding marks have been initially made. A ground cover of 10 cm proves to be an convenient long term protection. A better one is to use a cylindrical box covered by the ground and protecting the benchmark from the direct strain of the top layers (e.g. if a truck passes over it).

* It is also quite useful to prepare in a semi-permanent way the locations for the rods between the benchmarks. These points will be considered as provisional standpoints, that will not move noticeably during a few hours or even a few days, and will serve for the rods so that at every operation the geometric conditions will be quite similar.

The observations will be generally of the highest precision possible for the first operation, and for the next ones it will be in accordance with the magnitude of the movements. For the first time, a double run (forward then backward) will be used, with little attention paid to the slowness of measurements.

The precision that one may reach when all possible precautions have been taken is possibly up to 0.1 mm/km (in flat areas). The main applications of high precision levelling for volcanoes are the search for phenomena of inflation/deflation of the ground related with changes in the strain pattern linked with the evolution of magma (variation of pressure in a zone of storage if cooling and crystallization occur, interactions between the water table and a magma body moving upwards, etc...). The resurvey of a levelling line will provide us with the tilt of the ground, of course. But the specific interest is to show the spatial variation of tilt. This information is of primary interest if we want to localize the geometric place of the center of the variation of strain in the ground.



In A, zone of maximum horizontal dilatation strain

In B, zone of maximum tilt

We know for example that when this center is at a depth of D, the vertical deformation pattern displays a maximum of elevation change above the center (so that in this zone the related tilt is very low), and the interesting feature to notice is that the maximum tilt is approximately at the same horizontal distance from the vertical of this central point. So it is extremely useful to get not only the tilt, but its spatial variation in order to find where is the center of strain change.

If we summarize the main features of this methodology, we must notice that:

* The first operation is quite expensive and may require many days of work.

* For this reason we must already have some a-priori ideas concerning the planimetric localization of a possible center where strain is likely to change before the levelling network is set up. If the "ring" of maximal tilt does not cross the network, this one in-fine is useless. Such a set up must occur after preliminary studies of the zone, for example seismological ones.

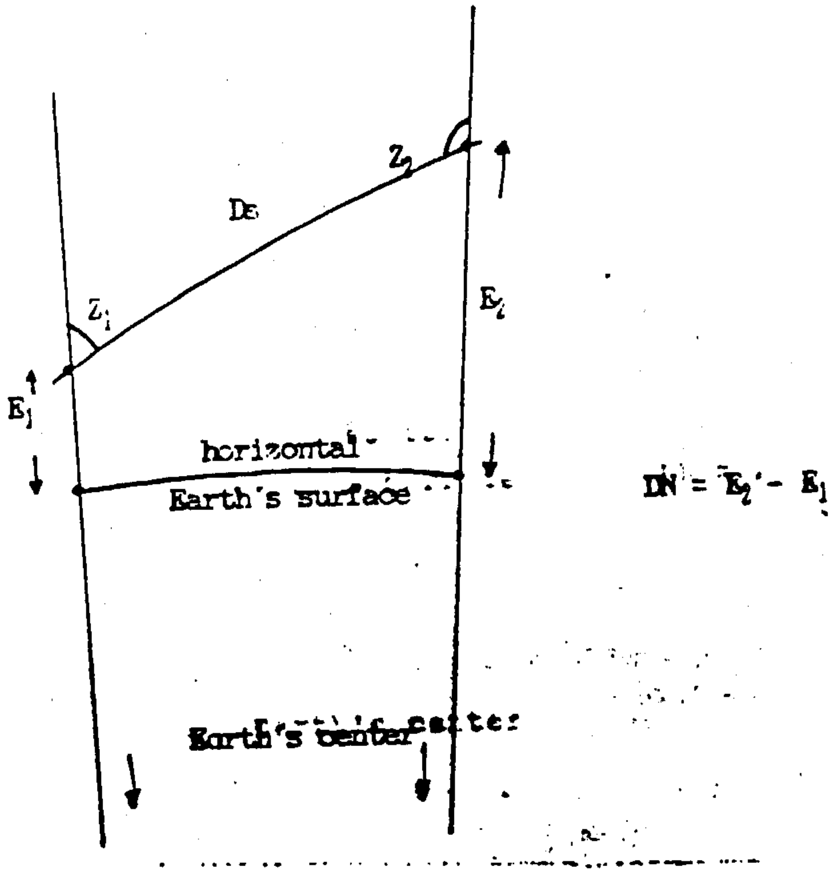
* The reobservations need not to be performed the same way as for the first time. It may be done in two steps: first some local "tests" with good precision between a few pairs of benchmarks. Then if the movements are not perceptible, we may decide to wait more before a global reobservation; and if they seem strong, the reobservation may use less precise methods like trigonometric levelling, with a much better speed and lower cost. Only if movements are small we must reobserve with high precision methods. The reobservation methodology must be optimized with respect to the amplitude of the movement to detect.

* When the measurements are performed on very active zones, one has to be aware that vertical movements may occur during the observations, so that the quality tests (e.g. misclosures) may look abnormally bad. In such cases, it is advisable to go fast and not to look for the maximum precision which is always expensive and in this case useless.

I.4. Trigonometric levelling

This approach is not yet classical, even if it is probably going to be more and more used under its motorized form (High precision motorized trigonometric levelling, used for the first time in France,1982). It needs the use of two theodolites and an EDM instrument. The two theodolites, set up at two stations several hundred meters distant, are aimed at each other at the same instant. The two vertical angles Z1 and Z2 are measured, then the EDM provides the slope distance Ds between the two instruments. We have no special model of refraction to assume, only have we to suppose that the radius of curvature of the ray path is constant. It is easy to show that the denivelation DN between the axis of the two instruments is given by:

$$DN = Ds \cdot \sin(Z1 - Z2) / 2$$



In fact, the assumption that the curvature is constant is not perfectly true, and it is the only limitation of precision. But for distances up to 500 m between the instruments, and regardless of the denivelation, the precision may be around 1.5 mm/km, which is comparable with direct levelling's one. But the speed of measurement is considerably higher, especially in mountainous areas. For volcanology, this method is very convenient for:

* Fast reobservation of an old network with ordinary precision. It will be up to 10 times faster than classical levelling.

* Set up and reobservation of special levelling networks (like large dry-tilt stations) on the flanks of a volcano. Even if the slopes are quite steep, the results will be good. And it is often impossible to use direct levelling in these circumstances, because of the poor quality of the ground, the difficulty to observe and the simple duration of such operations even for small networks.

* It is a quite convenient solution to provide precise heights for a reobservable gravimetric network on the flanks and the surroundings of a volcano.

The instruments to be used are automatic high precision theodolites (WILD NT2, KERN DKM2 for example) or even better, electronic theodolites which are much more easy to use (presently the only convenient ones are the KERN E2 and WILD T2000 or T1600). The EDM has to be a classical compact instrument compatible with the theodolite. Some small mechanical modifications will be made so that we may fix a reflector on the theodolite easily, at the same distance of the rotation axis than the EDM is, and large targets are centered around the front lens of the telescope of each theodolite. That way the measurement is very fast and accurate.

This levelling method should be preferred now every time when the maximum precision is not absolutely necessary, as it is much cheaper and quicker that anything else at this level of quality. Its only bad features concern the cost of required instruments. The direct levelling commonly uses quite unexpensive ones: even the best levelling instruments do not reach the quarter of the cost of a trigonometric levelling equipment. But this remark must be moderated by this other one, that theodolites and EDM are useful for many other applications.

I.5. Dry Tilt

This methodology is derived from high precision levelling, but anyway it seems convenient to present it in a quite detailed way. In order to keep an easy presentation, the reader will find a complete presentation in an annex (viz. Annex I).

Dry tilt provides a solution to get local tilt informations. If the observations have to be performed often (weekly or daily), it must be compared with the use of recording or teletransmitted electronic tiltmeters. The dry tilt has a very low set-up cost, many times cheaper that the one for the installation of a tiltmeter. Anyway, the running costs are quite unfavorable to dry tilt stations, even when we take into account the maintenance of electronic instruments in the field, always expensive. A tiltmeter gives quasi continuous informations, with the same quality level, so that it is often much more useful. A good way to optimize the tilt measurements on a volcano is to begin by the installation of many dry tilt stations, say ten for example, then after a few months or years of data to choose with regard of the results a few good places where the deformations seem sensitive to the volcanic activity, and then to install some tiltmeters in such places. If no telemetric facilities are available, recording autonomous stations are a good solution. But the best is to use ARGOS satellite link, because of the little number of data to transmit, the ruggedness and low cost of this methodology. Obviously, if radio links are already available, for seismic stations for example, it is more convenient to exploit them. But anyway in such cases, the use of dry tilt stations will be a wrong solution, as it asks for an important manpower of well-trained people, and at long term it proves to be very expensive. And in crisis period, it is preferable not to send people too close from the possibly active parts of the volcano, so that generally dry-tilt does not provide properly the useful short-term informations.

On another hand, when many places have to be surveyed very rarely, just for scientific studies of the general behavior of an unknown volcano, or when the local people cannot be dissuaded to destroy or to steal electronic instruments left in the field, dry-tilt is very convenient. Anyway, no tiltmeter station should be installed without a nearby dry tilt station as a back-up in case of failure, readjustment or destruction of the electronic apparatus, so that the long term performance of this place will not be lost.

I.6.Use of tiltmeters

Many physical phenomena may be used in order to record small geometrical movements of an instrument around the vertical, because the imagination of men, and especially physicist's one is without limits...We may use LVDT (Linear Variable Differential Transformer), water-tube level with capacimetric, piezometric or electromagnetic transducers, interferometric systems with a mercury mirror, quasi-vertical axis pendulums, etc...

Whatever the technology used is, the instrument has generally a very high accuracy, a good precision for short periods, and a long term stability which is always poorly known and difficult to check. When no special attention is paid to these possible drifts and sensitivities to DC supply or thermal changes, some instruments evidence a complete impossibility to give the long term behavior of the station.

But if the sensor is correct, another problem may be a source of trouble for the user, namely the local noise of the station. A tiltmeter samples only a very small portion of ground so that the choice of the best place is very delicate. Let us just remember that a sensitivity of 1 microradian for an 1 cm wide apparatus means that we monitor linear movements of about 1/100 th of micron, which is exceedingly small. So we must not be surprised to see that thermal noises or rainfalls may cause unwanted tilt effects that may amount up to hundreds of microradians in bad cases, as soon as even an almost imperceptible microfissure of 1 micron wide is present in the rock where the tiltmeter is bolted. The larger is the instrument baseline, the more it is insensitive to these spurious phenomena. For that reason, water-tube tiltmeters do not experience these local noises and present a much higher ease of installation. It means also that a high attention must be paid to the settlement of the instrument, and that the only way to check the quality of the location is to monitor the results for a few days, or more if possible. The main difficulty is to find a good rock firmly anchored into the ground, without any microfissures at a few tens of centimeters from the fixation of the apparatus, and correctly insulated against thermal changes in order to limit the meteorological effects (underground installation, lava tunnels for example).

If we evaluate the features of electronic tiltmeters, we find out that they are a bit costly, so that it is not possible to consider them really as consumable small equipments. But if the transmitting or recording system has been correctly designed, it may provide years of valuable data at a very low cost, particularly with ARGOS satellite links. Anyway the choice of a good site is uneasy, and in fact it is complementary from dry-tilt stations with which it should be always associated.

I.7. Use of tide gauges

Another convenient way to get tilt informations in some places is to use two (or more) good mareographs or tide gauges if an important lake or sea cost is at an immediate proximity. This case is not quite usual, if we except the crater-type lakes. These ones are generally of poor interest, as the banks provide only possible locations where the expected tilt is very small, too near from the probable center of symmetry of the deformation, and at the same distance from it. Thus we probably will not experience any probable differential movement. But if it happens that such a water surface is available, then we must not forget that two or three instruments able to monitor the relative positions of a point of the ground and the surface of the water will give us an information of tilt for the figure formed by the instruments (e.g. Lake Myvatu, Iceland).

Many ways to measure the level of water exist. For example, one may employ float mareographs, but their precision are mainly limited by the maintenance problems of the float. We may use quartz piezometers, but the results are difficult to correct of atmospheric pressure variations and it has been up to now impossible to find sensors with a negligible long term drift. We may use systems measuring the pressure of air bubbles emitted continuously underwater at a fixed place, but this measurement too is not free from long term variations, and a gas supply has to be regularly provided. Another solution is to observe with ultrasonic waves the distance, in the air or in the water, between a ceramic sensor and the water surface which acts as a reflector. Here the only problem is that the speed of sound in atmosphere or in water changes considerably with temperature, pressure, salinity and so on, so that the transducer has to be close from the surface (in order to limit the importance of the uncertainty due to errors on the sound celerity), and this is a limit if level variations are large.

One may conclude that this type of measurement cannot be very precise, namely 1 cm for each station; but another solution may be used, more expensive but more precise too. We have observed since many years that EDM instruments could give a very convenient measurement without reflectors if they are orientated vertically so as to be in autocollimation over the water surface. The air-water interface reflects 3% of the incident light, and this is far enough to activate the receiving electronics so as to measure the distance between the EDM and the water. We need no physical contact with the water, the precision is excellent (down to 1mm with some instruments) and so is the long term stability. The main difficulty is that a special mechanical mount must be provided at each location, and that the EDM is an instrument whose cost is higher than classical mareograph's one. But a convenient possibility is to move the EDM from place to place if the access is easy, so that such a network will be measured from time to time like a dry-tilt network. Another solution is to start the EDM once or twice a day and to send the measurement via ARGOS satellite link. It allows to have maintenance free autonomous beacons (with a very low DC power consumption) and an easy access to the data in a centralized way.

This application of mareography must not be forgotten when the magmatic reservoir is supposed to be very far from the surface, as any change of strain in this reservoir will create a deformation pattern spread on a large area and quite uneasy to monitor. This equivalent of a very long baseline water tube tiltmeter may prove extremely useful if a large water free-surface near the volcano is available.

II. DETECTION OF HORIZONTAL MOVEMENTS

II.1. Introduction

The same type of analysis we have already made for the detection of vertical movements has its equivalent for the horizontal ones. We will see that we can reobserve old networks or adapt classical methods in order to optimize the work on volcanoes. Anyway we must point out a very different behavior of the atmosphere concerning the deflexion of a ray path if we consider horizontal or vertical angles: as it was explained previously, the ray will stay in a vertical plane even for long distances, because the gradient of refraction index is generally perfectly vertical. So we often do not care about the consequences of the presence of atmosphere, especially for triangulation. And this geometrical situation of the effects of refraction has led to the use of the theodolite, which separates completely vertical and horizontal measurements, and with such a method it is useless to know the altitudes of the targets when we have to measure their planimetric positions. This is the cause for the traditional discrepancy between planimetry and altimetry in geodesy. But this separation is now sometimes obsolete, because we use more and more EDM distance measurements which are much more complicated to process in a network (but it does not matter, because of the wide use of computers now). And measurements of distances lead us to mix horizontal and vertical aspects into a whole tridimensionnal network, because they physically do not separate any longer planimetry and altimetry.

The other main feature for today's geodesy is that we have for the first time the way to reach the 0.1 ppm level, that is to say 1 mm of precision at 10 km distance, with two-colors laser EDM, and this level of precision is of outstanding interest for volcanological studies.

II.2. Resurvey of geodetic networks

We may always use an old existing national geodetic network and resurvey it in order to monitor the ground deformation. But this is not stricto sensu the equivalent of what we mentioned for resurveying levelling networks. The geodetic networks are basically used to get a frame for mapping purposes, and thus do not require a high precision when we compare them with levelling networks. In fact, it is rare that the precision of a national geodetic network is better than 10 ppm, that is to say 1 cm by km of distance between the points we consider. And it is sometimes worse. Another general feature is that the areal density of points is often so low that on a given volcano, one has little chance to find more than one old point. And we also must notice that with classical geodetic methods one will never set up any point on a volcano except on the summit, as it is the only place, with such a conic shape, where it is possible to get a correct intervisibility with other distant stations. And with the model of deformations we have previously explained, we do not expect any horizontal movement for a point near the center of the probable deformation field pattern.

Thus one will easily understand that only in a few cases will it be possible to resurvey in an useful manner part of the national network. The drawing of this network may nevertheless be used sometimes when the topography is difficult and when one might spend a lot of time to find a good location for benchmarks with a non questionable intervisibility . Even if the quality of old data is so inadequate that it proves to be useless for further comparisons, we have the certainty that from one point to any other neighboring one, the line of sight will not be interrupted except by the vegetation close to the points. This consideration may sometimes allow the surveyor to save a lot of time.

We must notice something else concerning the old coordinates already published. Due to the difficulties that geodesists experienced only a few tens of years ago to compute least-squares adjustments of large networks, it appears often that the original raw observations, when available, may allow us to compute a much better set of old coordinates than the already published ones, as calculations have been for centuries the weakest part of the art of geodesists. The use of successive (first, second, etc.) orders for geodesy is also the essential consequence of that weakness. As a consequence when we get such observations, only triangulation with just a few baselines, when comparing new observations with old coordinates, it is of outstanding interest to use the old observations instead of the old coordinates, to adjust them with an approximative scale, to deduce from these operations the expected precision of ancient data and then to compare the results with the recent measurements. This way to process data seems presently the most efficient and simple solution when one tries to retrieve a maximum of informations from an old geodetic survey.

Another aspect of such calculations is the method we use to display the deformations in the network. Although during a long time an extensive use of displacement vectors has been the rule, it appears now that many other solutions can be used as well. The difficulty arising with displacement vectors is double:

* It is necessary to choose one point (or one set of points) supposed fixed, and the same for one direction which will be invariable. These choices prove to be somewhat difficult: when improperly made they may conceal an interesting movement under, for example, an artificial rotation of all the network.

* Even if error ellipses are commonly used to display the confidence level on the results, it has a statistical sense but little physical one, because of this preliminary choice of a fixed point. And it is not possible on such a display to appreciate the significance level of the relative

movements between two points except if one of them is the fixed one.

So we presently recommend to display the deformations using strain tensors with a direct representation of errors using a Monte-Carlo methodology, then if necessary after a first interpretation of these tensors to use displacement vectors as an easy-to-read complementary display (viz. Annex II where the practical aspects are developed).

II.3.Triangulation

The most traditional solution to observe a network is to measure angles with a theodolite, and with simple trigonometric rules we can compute the whole network. In this paragraph we are not going to explain the theoretical aspects of this well-known procedure, but we shall just emphasize its specific features compared with other solutions.

* First of all, the theodolites are opticomechanical instruments widely used since forty years and even more, they represent an excellent optimization in terms of industrial know-how, they nearly never experience failures, except after strong shocks perhaps. So their ruggedness make them very convenient for field work. Compared to that it is not rare to cancel an EDM measurement because of a low battery voltage...

* The precision of measurement with good instruments may reach 2 ppm, that is 2 mm by km of distance between the stations, combined with a very small-variance error of centering, around 1mm for example. If we compare with EDM whose error pattern is commonly 1ppm and 5mm, it appears that for small networks (<3 km), it is often more precise to triangulate than to measure distances, except with high-precision EDMs.

* The theodolite observation needs a good training in order to be correctly performed, much more than EDM's one. But the new generation of high precision electronic theodolites

(KERN E2, WILD T2000 or T1600) proves extremely easy to use, so that this remark is no longer true.

* Triangulation do not need simultaneous meteorological observations to yield its best accuracy. The targets are passive and may be very cheap, almost expendable, so that the observer may be autonomous. With EDM one needs another people near the reflector to measure temperature and pressure, and the reflector with its mount is not a cheap target so that it must not be left unattended in the field.

* Triangulation is complete only when several points have been observed, and an unexpected interruption of measurements (bad weather) may let the surveyor with a set of data impossible to compute. With EDM the interpretation of partially observed networks is much more easy.

* It appears anyway that distance measurements are less difficult to manage. And when many people are available, the observation cost with EDM is somewhat lower than triangulation's one, but it is mainly a question of training of surveyors.

II.4.Electronic Distance Measurements (EDM)

The EDM appeared in the late 1950's but really got widely used 20 years after, when they became so compact that they could be attached directly to a theodolite. They measure the time for the light to travel between the instrument and a reflector, and convert it into a distance provided the surveyor has previously observed the speed of the light in the atmospheric conditions prevailing during the measurement. This speed is computed under the designation of refraction index, from measurements of mean temperature and pressure along the ray path. The main remarks one has to keep in mind when performing such measurements are:

* The acquisition of meteorological data is an important part of the whole process. We must keep in mind that errors on mean temperature and pressure induce proportional errors; for example 1 ppm is the consequence of 1 degree error on temperature, or 3 mmHg (=4 mbars) error on pressure. The main rule to observe is that these data should be measured at least at the two ends of the line. The barometers must be checked once a year, the thermometers too, and the temperature measurements must be performed as high as possible above the ground (4 meters is a good value). The temperature sensor must be in the shade for good measurements, and when the wind is irregular so that the temperatures varies quickly, the best values are always the lowest ones.

* The EDM must be calibrated with its prisms once a year, using a 3 or 4 stations aligned network (viz. Annex III), without any need of already precisely measured baseline. We can use any sort of prisms, but it is preferable to have a mechanical mount allowing a good orientation in azimuth and site, especially on volcanoes where vertical angles are sometimes far from the horizontal. Every type of prism has its own constant, so if we change the type of reflector we must change the constant.

* It is very important to measure carefully the heights of EDM and reflectors at each station, and it is necessary to get the altitudes of the points for processing of the necessary reductions, and for any global adjustment. This feature is quite different from the triangulation where such data are useless: here they are necessary. For example each distance must be corrected in order to be reduced as if it had been measured from the level of the benchmarks and not at the level of the tripods. If the elevations of the stations are E1 and E2, and the heights of instruments are H1 and H2, the value of the correction is approximately:

$$D \text{ corrected} = D \text{ measured} - (E1 - E2).(H1 - H2)/ D \text{ meas.}$$

* The model of errors for EDM is a combination of:

- A fixed variance noise due to the instrument, ranging from 5mm for most cases down to 0.2 mm for some high-precision devices (GEOMENSOR from COM-RAD, MEKOMETER ME5000 from KERN).

- A proportional error due to the imperfections of the frequency standard of the instrument, ranging from 3 ppm commonly and decreasing to 0.1 ppm for the best devices.

- A proportional error due to incorrect appreciation of meteorological data, often amounting up to 5 ppm, but that may be limited when conditions are good to less than 1 ppm (cloudy and windy weather, night for example).

* The EDM provide very convenient ways to survey from a distant station the horizontal deformations of the top of a volcano, if we fix definitively prisms in some places and if we set up a device able to teletransmit the temperature near the reflectors to the other end of the line. The pressure may be deduced from the pressure at the EDM station, as the difference of pressure is nearly only a function of the difference of height. If the temperature is not available, the measurements will generally be of poor precision. Anyway if one of the reflectors is supposed stable (far enough from the active zone) and experiences the same meteorological conditions as the other points, it is possible to cancel the main part of the errors by computing the ratio of each of the distances to the distance supposed stable. This value will be error free, except if this "stable" point actually moves, but this last aspect may be checked from time to time by sending someone to measure temperature near the reflector so as to allow to perform a good absolute distance measurement and a test of stability for this line.

* EDM may also be used as large strainmeters if one wants to monitor a series of faults amounting to a few hundred meters. The instrument and the reflector will be set up in a

permanent way with an insulation against humidity. The EDM a. a thermal sensor are activated e.g. every hours, the result is either stored or teletransmitted, via ARGOS for example.

* We have already mentioned that EDM could be used to monitor water level like mareographs, but also in the wells of a given area. It has been shown that in some places, changes in the water-table level could be strongly correlated with eruptive processes.

* A new generation of EDM is presently available, the 2-wavelength instruments. They measure simultaneously the optical paths corresponding to the same distance with two different colors, because of the variation of refractive index with the wavelength. These instruments prove to be extremely precise, around 0.2 mm of fixed-variance error combined with 0.1 ppm of proportional error, because they actually measure the index of refraction experienced by the ray. Such EDMs are probably the best solution we may use to monitor the deformations of the summital part of a volcano from the basement. At a distance of 10 km they will provide a precision of 1mm, and it must allow to detect very small movements in an easy way and at a very low measuring cost.

II.5.Use of strainmeters

The strainmeters are the equivalent of tiltmeters for the monitoring in a quasi-continuous way of linear movements, for example across faults. Their advantages are that they will provide the kinetic aspects of a given phenomenon, but their very short baseline expose them often to display a lot of spurious movements, as it is common with every local instrumentation. Another difficulty arises when one wants to record the movement of a fault system, when many parallel faults are visible. If the strainmeter crosses only one of them, in many cases this very one will not be active, but the next one a meters distant will be. To summarize, let us just remember that a good place is always very difficult to choose.

The physical methodologies used are also very different:

- We may fix bolts in the rock and measure their positions with a micrometer. This is not a recording device, but it is cheap and easy to use.
- We may use mechanical devices with invar wires, and monitor the change of length continuously even with just a rotating drum, or better with a data recorder.
- We may use a lot of electronic devices, among which LVDTs are often used, or even optical interferometric methods. We can whenever necessary measure with accuracies nearly as high as we want (up to 0.000001 micron for example) but obviously it is useless. Here also, the settlement of the instrument is as important as the device itself.

Up to now strainmeters have not been widely used on volcanoes. But EDM strainmeters previously described, although expensive, are perhaps among the best possible ones as they are very easy to set up.

II.6. Simplified methods

One should not forget that there are plenty of simple ways to acquire deformation data when movements are large. The use of high precision instruments is sometimes useless. Let us just mention a few possibilities:

* Use of alignments. If we want to monitor the evolution of a lava dome, we may draw large marks with paint on some lava blocks and observe their position with respect to natural details (e.g. trees, rocks, etc...) from a given place.

* Measurements with measuring tapes, for example across a fissure swarm, between bolts that we have fixed in the

surrounding rocks. If the field procedure is convenient, one may reach for the monitoring of the movement an accuracy of one mm even for distances of several tens of meters. But the people in charge with such operations must very carefully operate in the same way at each operation, so that the various errors are nearly the same in every remeasurement and they cancel each other for the comparison.

III. TRIDIMENSIONAL METHODS

The so-called tridimensional methods do not consider the local vertical as a particular direction, and ipso facto they provide complete geometric informations about one given set of stations. We shall consider the only ones that we may expect to use on a volcano, photogrammetry and spatial geodesy. Other ones as Satellite Laser Ranging or Very Long Baseline Interferometry (VLBI) are not available for field work up to now.

III.1. Photogrammetry

The photogrammetry is a way to use photographic records in order to calculate geometrical positions of various objects, whose dimensions may be extremely variable, from a few centimeters up to tens of kilometers. It is a way to store the positions of optical rays at a given instant, and to exploit these records later. It needs the use of special cameras able to take pictures characterized by a stable and well-known distorsion pattern, so that they are called "metric" cameras. It is a very specific topographic methodology, and it requires a long specific training with big and expensive instruments. Once again we suppose that the reader has already some preliminary knowledge about these topics, and we suggest that he may read one of the numerous technical textbooks already available if necessary. We must be aware that everywhere in the world we may find specialists of photogrammetry able to process data for volcanology, so that the volcanologists have not to become photogrammetrists...

The basic use of photogrammetry is the drawing of maps. We shall present here some applications of this methodology which are not classical ones, but have proved extremely powerful and useful in detection of ground displacements.

The fundamental principle is the following: let us suppose that with an appropriate device we are able to observe simultaneously two pictures of the same object at two different standpoints, one view for each eye. In such conditions we may notice that everything is as if we were observing this object with one eye at each standpoint, so that we see it with a three-dimensionnal aspect. The main problem arising here is that for a given couple of stereopictures there is an infinite number of relative positions of these pictures giving to the observer the sensation of stereoscopy. Among them only one is the exact replica of the oiginal geometry formed by the camera at the two different standpoints, that provides the exact appearance of the initial object. In order to achieve such a geometrical arrangment, it is necessary to get some precise coordinates for a few points of this object. Once this initial set-up of the pictures is correctly made, the work is just to make the appropriate measurements on the stereoscopic image in order to describe the object in a suitable way. Generally the "object" is the landscape, but it may be anything else. We call "aerotriangulation" the way to compute the relative positions of the pictures from the coordinates of some well-identified points of the object.

III.1.A. Retrospective Photogrammetry

This is a way to exploit at maximum old available metric pictures in order to measure the ground deformations that occurred between them and more recent ones. Many aspects of such a work merit some discussion, for example:

* The work to be done is the following: First, we must find some points of known coordinates in the surroundings of the interesting zone. Then an aerotriangulation is performed separately on each set of pictures so as to allow one to get strong geometrical constraints for each pair of stereopictures. Then on the best quality set (often it is the most recent one) we compute the coordinates of a series of "fixed" natural points all around the useful area. Then we impose the same coordinates

for the corresponding points of the other set. Then we measure the coordinates of presumably mobile natural targets (for a landslide) or we get profiles by intersection of the ground by fixed reference planes (for estimations of volumes of lava), for the two sets of pictures. The comparison of these coordinates allows us to measure the dimensions of the interesting phenomenon.

* It is sometimes very difficult to know the exact metric quality of the images we have to process, as the distortions of ancient optics are often important and unknown. Whenever it is possible, one must try to check the distortion with an aerotriangulation (specific computation process allowing to know the spatial position of each successive position of the camera) on a part of the scene where no movements have been likely to occur, using natural targets like rocks, corners of buildings, roads crossings, etc..., and comparing the results for the two sets of images. Even if a good model of distortion cannot be computed that way, it may nevertheless provide an acceptable estimation of the errors to expect on other processings using the same type of data.

* We cannot avoid to carry on some assumptions about the "stability" of certain areas of the scene. As the precision is often modest (a decimeter at best), the type of movements we try to detect are important ones. In volcanology, it means mainly the precise measurement of lava flows (outpoured volumes), and of avalanches from unstable lava domes. So the hypotheses of immobility are often hardly questionable for such an accuracy. But the technical problem is to find a large amount of natural targets which are really analogous for the two series of pictures.

* It is hardly possible to get in such a way an excellent precision, of course, but it depends merely on the scale of the pictures. For example with pictures at a scale of 1/30 000 it will be difficult to be better than 2 meters,

especially if natural points easy to aim at are rare (corners of houses, rocks, etc...). And the interest of such a work depends also on the time lag separating the series of scenes. If we get old data (since 1950 one may expect to find not perfect but acceptable metric images), the quality is not high but we have a view over a large time scale. In some cases it may be a fantastic source of informations. One must keep in mind that such pictures are available in several countries, often at scales around 1/30 000, and that old images are generally stored when accessible at the national office in charge of the cartography. For large movements (landslides, glaciology, etc...), we must also remember that satellite images may be exploited so as to measure ground movements or changes of shape: with SPOT pictures, we can reach the precision of 5 meters, that sometimes may be helpful, the position of the topography and its changes, for example if we want to appreciate the exact importance of mass transfers for an andesitic eruption, measurement of a lava dome growth, quantity of ejecta in an important explosion, etc...

In conclusion, the retrospective photogrammetry is not a high precision methodology, but it should not be forgotten when old metric images are available.

III.1.B.<u>High precision photogrammetry</u>

This methodology is a very recent one, mainly linked with the progresses of aerotriangulation and availability of powerful computers. The principle is to establish in the field before the pictures are taken a large number of targets. The pictures are made with a very large longitudinal and lateral overlap, minimum of 60%, so that the image of a given target will be visible on many pictures (6 for example), and part of the targets are positioned with high precision geodetic methods. After an aerotriangulation that for some works will need a considerable computation power (several tens of thousands unknowns sometimes), one will get the coordinates of all the targets. For example, on a zone of 6km x 3km, where 350 targets have been set up, a good precision geodetic survey is performed for 12 targets, providing an indecision of 2cm on the whole area for them. Aerial pictures are made at the 1/5000 approximative scale, with 85% overlap. After the aerotriangulation we get nearly the same indecision level for the 338 targets as for the 12 previously determined ones, namely 2cm. We shall point out some of the specific features of this methodology:

* The field targets must be cheap, present a high degree level of immunity against possible destructions, be able not to move during a few years and have a convenient dimension (depending on the scale of pictures, so that their images be easy to observe accurately in the photogrammetric comparator, e.g. 60 microns on the picture), be white with a design allowing a good contrast against the natural background. If the ground is clear (sand, dacitic ash, ice for example) they must be white circled with black, if it is dark (lavas, grass, basaltic ash, etc...), just white. As the targets for such a survey play the role of the benchmarks, it is easy to understand that it is not always easy to design them. When possible, a good solution is to paint directly on some places with the help of a circular shape a paint for outdoors walls. The only precaution to take is that the perimeter of these disks must be approximately in a plan (no more than 2cm departure from flatness), but it does not matter if the central part of the disk is far from the plan and if the plan is not horizontal. In other words, the image of the target must be an ellipse. This allows us to find easily rocks to be painted. Another solution is to fix with bolts thick plane plastic targets, in zones where the risks of human destructions are not too high. The targets must be placed according to the positions of the pictures, with a minimum of 15 on each of them (3 lines of 5).

* The cost of the first operation is important, as it is necessary to set up all the targets, to carry on the geodetic survey, to take the pictures and to process them. But we must notice that the cost per point is very low, compared with other methods. On another hand, we observe that it is necessary to determine an almost uniform density of points, so that the number of targets has to be important by technical necessity. Thus the full interest of this methodology is reached only when it is advisable to survey simultaneously a large number of regularly spaced points. Anyway the cost of the next field operations (resurveys) is quite low, and it is not possible to find any cheaper solution at this level of precision.

* This method is especially convenient for monitoring deformations on large areas in a very short time, for example when good meteorological conditions are rare so that field work is very uneasy. The aerial survey is very fast and the associated geodetic determinations may use spatial methods like GPS which do not need a correct visibility to work properly. (Anyway one must be careful when mixing vertical data from different origins, for example levelling and GPS, as they are of a completely different physical kind: levelling gives informations with respect to the geoid, and GPS with respect to the ellipsoid !). Thus we have an excellent solution for testing the behavior of the summital part of a volcano. The large number of available points where the deformation is measured allows to get an excellent mechanical model of movements, and we should not fear the local noise due to instabilities of the targets. We have a large number of data in order to check these aspects in a statistical way, and the "sampling" of the natural medium is much better than with geodetic methods.

* The photogrammetry in general and this method in particular might only be employed by specialists. The instruments used for restitution of stereopictures are quite compli-

cated and need highly trained technical people to be correctly operated. If such a type of work is to be done, it is necessary to establish an efficient link with an institute specialized in photogrammetry. The scientific staffs interested in deformation studies may operate by themselves a lot of topographic methods, but generally not this one.

III.1.C. Terrestrial photogrammetry

All the applications of photogrammetry we have previously mentioned use metric cameras, but the general case is supposed to be the airborne use. The camera is operated in a plane, with the optical axis approximately vertical. Nevertheless it must be known that it exists also terrestrial metric cameras, which may be operated in the field so as to avoid the service of a plane, always expensive. The main problem when we want to use them is that it is rare that the topographic features authorize their use. Only if the slopes are very steep or if we have a good point of view thanks to a building or a cliff, such a solution may be envisioned. For example it is possible to monitor the mechanism of a landslide or of a lava dome growth if we find a place overwhelming the site. But this condition is not sufficient. For such cases, we have only a very limited choice of possible locations for the camera, and these places may not be convenient as they impose the scale of the pictures, the relative positions of the optical axes for the successive locations of the camera, the number of pictures to take in order to have a stereoscopic cover of the useful scene, etc...We have to remember that many technical essential requirements exist and we must know them:

* The focal length of the camera is fixed, the choice of focal length is often not very large (WILD P32, ZEISS UMK).

* Long focal distances are not available. So if the scene is far, the scale will be small and the precision of the survey will be poor.

* The stereophotogrammetric analogic plotters often do not allow to process terrestrial images, i.e. that have not their axes quasi-parallel. In most cases they will not allow to plot pictures whose axes are not parallel, for mechanical reasons. And sometimes it will be very difficult to have the axes parallel when taking the pictures.

The only photogrammetric plotters allowing to process every sort of metric pictures regardless of their positions are the analytical plotters, which use mainly a powerful real-time processor and perform with software all the work previously made by mechanical means on classical plotters. Whenever exclusively classical plotters can be used, one has to be aware of these aspects when taking the pictures, otherwise data may prove impossible to be processed properly afterwards. If we take correctly into account these contingencies and if conditions are favorable, terrestrial photogrammetry appears to be a very convenient and cheap methodology to get the pictures.

III.2.SPATIAL GEODESY

III.2.A. Global Positioning System

Many satellites have already been launched for geodetic purposes, but only a few systems are available for high precision positioning. We must mention Satellite Laser Ranging and Very Long Baseline Interferometry (VLBI) but these solutions are presently extremely expensive and uneasy to use, and are often used in fixed observatories. The main methodology to present here is the Global Positioning System, using a constellation of 18 Navstar U.S.satellites when completed (presumably in 1992), and already usable now a few hours every day. The satellites broadcast accurately dated informations on two frequencies (1.2 and 1.5 GHz), and the receiver has the task to compare the data received simultaneously from a minimum of 4 satellites. It may be shown that it is then possible to compute the geometric position of the receiver in a geocentric frame. One can remark that vertical data are only geometrical ones (with reference to the ellipsoid), and this feature is quite different from terrestrial levelling which provides data with reference to the geoid. A rapid error analysis shows that we expect three main origins for the uncertainties:

* The orbit error due to the low quality of the broadcast orbits. This error is strongly diminished when one uses relative positioning between two receivers not very distant from each other (less than 100 km for example). But the highest precision is never attainable without the use of a devoted tracking network, composed of a minimum of 3 receivers located in places whose coordinates are accurately known in a worldwide reference system. These coordinates must be obtained through SLR or VLBI measurements, and one may understand that it is also a costly operation.

* The error due to the ionosphere crossing, due to the rapid variations of the ionic density of the upper layers of the atmosphere, that induces a delay of propagation which is not very well modelled. The consequences of such errors are also strongly diminished when using relative positioning. But the highest precision needs the simultaneous reception of the two frequencies emitted by the satellites. The comparison of the received data allows a good correction of this unknown delay.

* The error due to the inaccurate knowledge of the refraction index for the first kilometers of atmosphere, mainly because of the extreme variations one may observe for the water vapor pressure and the strong importance of this parameter when computing this index. There are no good means to get rid of this problem, except perhaps when using relative positioning, as it may cancel between two stations if the atmospheric conditions

are similar (the minimal condition is that they are at the same height for example, and not too far).

The GPS has been set up by US army in order to provide an ability to find one's position within ten meters in less than one second. The worldwide precision is a bit better than 10 meters, which is generally useless for our purposes. But surveyors have found many possibilities to reach a much more useful precision, by performing long duration observations (one hour for example) and using only differential measurements. The error analysis leads us to the following:

- In a differential mode, with acquisition of meteorological data and around 1 hour of observations on 5 satellites simultaneously with one frequency receivers, we get a fixed variance of 5mm to 1cm for horizontal coordinates (depending on receiving signal to noise ratio) combined with a proportional error around 1 ppm (1 cm at 10 km). For vertical determinations, results are a bit less precise, depending upon the available satellite constellation and the tropospheric errors.
- If we use two-frequencies receivers and if we dispose of the precise orbits we may reach, with the same fixed-variance error, a proportional error of less than 0.1 ppm. One must notice carefully that this remarkable precision needs these <u>two</u> requirements. The use of dual-frequency receivers is an useless overcost if we have no access to the high-precision orbits. And this orbitography itself proves to be quite expensive. But its costs may be shared between many countries, if an agreement has been found previously.

GPS receivers are presently at a good level of industrial development. Even high precision instruments are not very heavy (less than 20 kg) and are easily operated on car accumulators. In order to process data, many software packages are available, allowing an easy computation on a classical PC microcomputer.

The last aspect to discuss concerning GPS is the optimization of the field work. First of all, it is necessary to have simultaneously a minimum of two receivers. Then, a possible solution is that one instrument will be located on a given trigonometric point ("fixed point") for all the measurements, and the other will be moved from place to place for one-hour sessions where 5 satellites are simultaneously visible. For a network of N points, this solution needs N-1 sessions. But each session will provide only a vector giving the relative coordinates of a point with respect to another one (the "fixed" one). So, in order to check the true quality of the measurements, it may be convenient to observe also the relative positions of two points, different from the "fixed" one. Such cross-measurements may appreciably improve the quality of the determinations and allow to get an evaluation of the errors.

If more than two receivers are available, observations are much faster. The field management must take into account the fact that during one session, a basic figure of 3, 4 or more points will be observed. So the successive sessions must link conveniently all these sets of basic figures in a strong network. For example if we compare a 4-receiver session to a 2-receiver one, it is easy to notice that with 4 we measure in one session 6 different baselines, and with 2 just one baseline: the productivity per instrument is considerably increased (three times in this case).

The conclusion we may draw is that it is advisable to have for every field work a large number of receivers. But the costs are high, and such equipments has to be fully employed if possible. The best solution is to share the receivers of many different institutes having a temporary use of this methodology, among a club of users. Each member owns his instrument(s) and borrows other member's receivers when necessary, in accordance with their respective plannings.

Among the various other types of possible topometric methods, what are the specificities of GPS ? We may note that:

- It requires a costly equipment, but needs little skillfulness from the field technicians.

- It has reached a good level of industrialization, but the weight and power consumption of the equipment do not allow yet to measure easily far from the roads.

- It is especially suitable for networks where intervisibility between stations is questionable. There is no longer any technical necessity to install the benchmarks just on the top of the hills.

- It allows to manage measurements without paying any attention to the meteorological problems of visibility. One can measure whatever the weather is, even in the fog or under the rain. This is very convenient when monitoring volcanic movements, as even steam vents will not prevent to perform a given planned work.

- The same receivers may be used for absolute positioning (within 10 meters), and this is sometimes helpful when it is not easy to locate a field device on the map, for example seismic or dry-tilt stations.

- Many erroneous ideas have been published concerning the precision. GPS represents a powerful tool for medium-quality measurements. For short distances, the fixed-variance noise is much larger than triangulation's one, and on medium and long distance networks, EDM are easily of the same level of quality if not better. But the ease of work is not comparable, as the benchmarks may be set up wherever useful, with little technical requirements (the antenna must see the sky with only a few masks over 15 degrees above horizon). But when the highest possible precision is to be reached, the GPS is often not the best technical solution.

GPS is the best solution only in terms of running costs because it saves a considerable manpower when compared with classical methods. And the full deployment of all the satellites to be launched up to 1990 will allow one to have a possible daily geodetic production several times higher than with another method. Here is the actual main interest of GPS.

III.2.B.Use of DORIS system

The DORIS system will begin on an experimental basis in 1989 with the launch by the CNES (French Spatial Agency) of the satellite SPOT 2. DORIS is a high precision orbitographic system composed of active ground beacons and a receiving unit on various satellites. Initially devoted only to orbitography, DORIS will also be tested as a high precision worldwide positioning system for some special beacons. After a lot of simulations performed in order to specify the expectable results, we suppose that the precision will be around 10 cm (absolute position) and for local networks around 5 mm of fixed-variance error (like GPS) with a very low proportional error, probably under 0.1 ppm. These values are quite comparable with the best 2-frequencies GPS results with a known orbit, and it is normal because of the quite similar error analysis we can do. But the very specific features of DORIS are the following:

- The field beacons are active, emitting several watts at 400 MHz and 2 GHz, and their electrical power consumption is therefore not negligible (but comparable to a GPS receiver). The results are sent in a quite centralized way, like ARGOS for example, up to the office, via a telex or a telephonic line. This feature is quite convenient for the surveying of many possibly active zones from a central Institute. The antenna of every beacon will be positioned from the satellite in a regular way so that even small changes may be quickly known. But the results are not directly available in the field.
- For geophysical purposes, special beacons have been developed, with a suitable conditioning so that they may

be left in the field with solar panels, the main part of the electronics (except antenna, of course) can be buried underground if useful. It is easy to see the nice case of application that it will be to monitor a volcano that way. If we suddenly have an interest for a newly active volcano, we may install 3 or 4 DORIS field beacons with the appropriate DC supply (if solar panels are not convenient, large capacity batteries may be employed for a few months). Then the deformation pattern may be known every day with an excellent accuracy.

- Another specification of the DORIS system which is less convenient is that it not possible to use simultaneously more than around 30 beacons in an area of 2000 km in diameter. This is a strong limitation for small countries with many active areas to monitor.

In conclusion DORIS could be in a few years an extremely suitable and efficient way, perhaps the best to monitor the tri-dimensional behavior of a set of benchmarks on a volcano.

- We have to adapt the design of the networks to the measuring devices already available. Generally deformation teams cannot afford the use of all the possible instruments, because of their cost. If we have a good level and no theodolite, we will use more dry-tilt and levelling, if we have a theodolite and no EDM, we may design a lot of permanent targets painted on rocks, etc... But what will be said now does not take into account such problems.

It seems presently that the leading ideas one should have when preparing for monitoring ground deformations on a volcano are to try to observe every change in the underground strain pattern. As this pattern is nearly always centered under the topographic symmetry axis of the terminal cone, the best solutions seem to be:

- To set up a basic topographic network, easy to resurvey, with at least a few dry tilt stations (with a minimum of 4 benchmarks at each station), and a few reflectors firmly and definitively fixed to good rocks under the top of the volcano, with 2 or 3 easy to access stations equipped with forced centering pillars where to aim at these reflectors. These pillars will be located near the basement of the volcano, so that the EDM distances range up to 10 km but not much more. They have no obligation to be in intervisibility, and their relative positions, supposed stable, will be checked if necessary with GPS campaigns every 5 years. From one of these pillars, EDM measurements will be performed often (weekly or monthly), provided a telemeasuring device will give the actual temperature near the summit. These measurements will be performed at night so that the meteorological correction will be more precise. If the data seem to show even a slight movement, the observations will be carried on from the other stations too, so as to complete the display of the movements and provide the errors on the results. The EDM data will be processed in two different ways simultaneously: absolute distances and ratio between each measurement and one of the distances (relative measurements, viz. paragraph II.4).

- If the activity of the volcano increases suddenly, or anyway if the interest for this area is maintained for a long period, some other networks will be set up. For example if possible some DORIS beacons, some levelling lines (high precision levelling), and some trigonometric levelling networks with up to 10 points on the flanks of the volcano. And we shall not forget to use more and more teletransmitted tiltmeters.
- If a good access is available to the zone that moves, a GPS network will be implemented, for example along the roads if any. That way one may get results even when the weather is cloudy or rainy.

IV.2.Installation of the benchmarks

Many ways to build benchmarks are possible, therefore in soft grounds the best one seems to be the following one: we dig a hole of around 30x30x30cm, then we drive 2 m. or even if possible 3 m. iron pipes in the ground with a big hammer, inside the hole, down to the level of the ground. For levelling benchmarks, one pipe is enough, but for geodetic benchmarks an excellent solution is to use three pipes, arranged to form a pyramid under the ground. Then the hole is filled with concrete and a stainless steel or brass bolt is fixed in it. If it is not possible to drive the total length of the pipe in the ground because of its hardness or compacity, we just have to saw the part of the pipe in excess. Such marks are easy to set up and have proved to display extremely small instabilities. Of course when big rocks are available, an easy way to get a good benchmark is to fix the bolt in the rock,obviously. But volcanic zones are often composed of very soft and unstable grounds, so that the choice is quite limited. Anyway, whatever may be the quality of these benchmarks, we must not forget that some local instabilities may happen and we must always keep the possibility to test this aspect of the measurements by a proper design of the observation procedure.

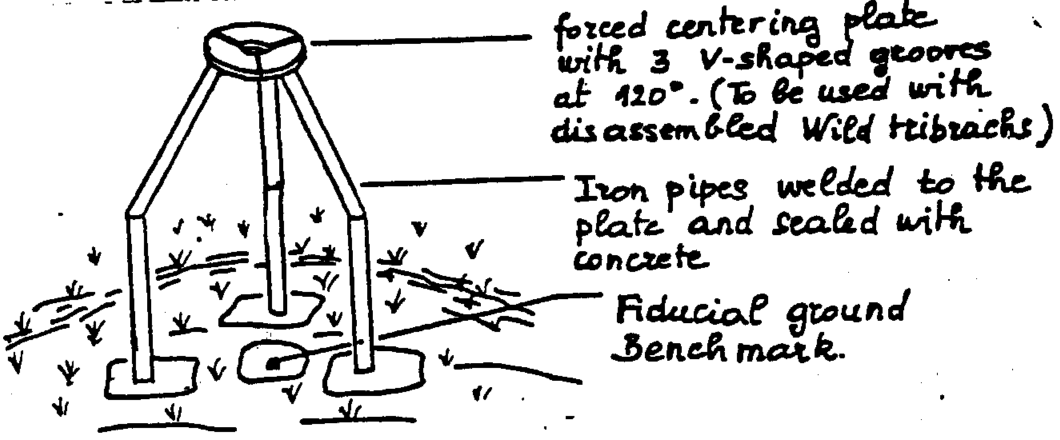
Another type of station commonly used is the pillar, and we have also to discuss this type of equipment:

* The main interest of a pillar is that it allows to save time for each set up, as it is no longer necessary to use a tripod. And if a special centering plate is sealed on its top, it provides a complementary way to save time, with a good precision.

* It is complicated to design a pillar so that it has little risks of spurious movements. First of all a strong basement is necessary. In soft grounds it may require around one cubic meter of concrete with the same system of metallic pipes driven previously in the surrounding layers. Then the pillar itself will be built with a piece of tube (minimum 20 cm diameter) filled with concrete and iron reinforcements linked to the basement's ones.

* For high precision measurements, pillars are often not the best solution. At the millimeter level, most of them are unstable, only sometimes because of the long term internal evolution of the concrete itself. If the maximum quality is required, it is much better to use a mark at the level of the ground than at the level of the top of the pillar. A solution is to use empty pillars, with a large hole inside allowing to be centered over a mark at the level of the ground, but we have no longer any solution of fast forced centering even if we keep the good mechanical stability of the pillar for the observations (useful only for triangulation). This solution is therefore not fully recommendable. Another possibility which already proved quite convenient is to seal with concrete a metallic iron tripod carefully coated against rust and corrosion (always very active in fumarolic areas), with a forced centering plate on the top designed with a hole in the

center. That way, after the initial fixation of this device, we can seal a bolt just at the vertical under the center of the top plate, using for example an optical plummet. If this fixed tripod is destroyed, we will not lose the station. If it moves because of local instabilities, it will also be extremely easy to check it at each set up. Therefore we combine the ease of use of a forced centering device with the security of a ground point, and with the ease of installation of a (a bit heavy obviously) tripod.



In conclusion, one must notice that many solutions exist to set up properly good benchmarks in volcanic areas, but that most of them are not classical to the point of view of the surveyor.

V. CONCLUSION

The detection of ground deformations, especially for volcanological purposes leads to technical solutions that differ often from traditional surveying sciences like geodesy and levelling.

A proper optimization of the monitoring methodologies is in many cases not so easy as one could have thought.

We must only remember that in these topics many possibilities exist when one wants to get one given information. But between various techniques, the cost of the information may vary from one to ten times depending on our choices.

Up to now, the volcanic deformations have generally been considered as a zone for scientific prospect and only rarely one has had the opportunity to analyze them in economic terms. But in many occasions it has been obvious that they are with seismology among the most important helps one can get when trying to forecast cataclysmal or simply dangerous eruptions, although not every volcano showed measurable deformations before erupting (maybe due to the lack of accuracy of the methods used). So when surveying programs begin, we must do what has always to be done when a laboratory instrument becomes a production instrument, that is a global optimization.

Another important idea to point out is the following: it must be clearly understood that in every geophysical methodology the result is of little interest when it is not possible to appreciate his confidence level. Sometimes it is known only in a quite approximative way (for example in seismology), sometimes it is almost unknown. All the deformation methods using topographic observations have this very specific feature in common, that they may provide a very good evaluation of the errors whenever necessary. Another aspect is that the result is a geometrical result, very easy to understand because it does not necessitate at all big physical models to be accessible to human mind. This is the reason why deformation measurements are widely used especially on volcanoes. But on another hand this situation is the origin of many (minor) difficulties: the theoretical aspects of these techniques are so easy to understand by everyone that many users do not suspect the possible importance of this processus of optimization, with a cost analysis.

In order to conclude, we are just at the beginning of a new science, the volcanological forecasting, and this science is in a period of strong progresses. Our concern is to find the best method to provide the most useful measurements in the cheapest way.

So we must wish good luck to all volcanologists-surveyors to find their own optimal path...

ANNEX I

DRY-TILT STATIONS

I/ INTRODUCTION

The so-called "dry-tilt" methodology is used to provide a way to monitor the tilt of the ground when some movements are suspected. It uses a quite classical topographic method, the high-precision or "direct" levelling. The instruments used are therefore a level, not necessarily automatic, and two rods. As the required precision is often quite high, the rods are generally invar ones and the level is equipped with parallel-plate micrometer. This papers reviews the various theoretical and practical problems that arise when one has to do such measurements for volcanological purposes.

II/ THEORY OF OPERATION

First let us consider two benchmarks, at 60 meters of distance of each other for example. If we measure the denivelation between these two points at the date T1, we find the value Dn1. Let us suppose that the ground is subject to a regional movement, so that it affects the altitude of the benchmarks. At the date T2, we will observe a new value for the denivelation, we note it Dn2. It is easy to notice that the only thing we may get from the comparison Dn2-Dn1 is the variation of the physical slope of the line joining the two benchmarks. We have no way to check whether a general vertical translation of the ground happened, superimposed over the abovementioned variation of slope. So we note that we have data to monitor only the variation of slope, we call that the tilt of the geometrical figure formed by the two benchmarks. It is very important to be aware of the assum-ptions we have made up to now. For example:

* We assume that the reference, which is the physical vertical, does not move whatever happens underground. This is generally true when the precision is not to high, but at a low level (around 0.1 micrord.) one may observe a lot of phenomenons whose effect is to deflect the local vertical: earth tides, oceanic tidal loading over continental margins, changes in the local geoid due to magmatic displacements, etc...For the precision involved in our measurements (around a few microradians), we consider that this assumption of an invariability in the direction of the vertical is true, but we must be careful if the precision increases noticeably.

* We interpret the tilt as the tilt of the ground, but this is true only if the benchmarks are correctly set up and move only when the surrounding ground moves. This is often very difficult to check, and we must be aware of this "sampling" of the natural medium, which is a permanent source of troubles for the specialists.

With these remarks present in mind, we may go further. With two benchmarks we compute the tilt angle TA with the formula, D being the distance between the benchmarks:

$$TA = (Dn2 - Dn1) / D \quad \text{in radians}$$

It is easy to notice that if the medium is continuous (no active faults), TA is independent of D and of the initial denivelation Dn1, so that TA is representative of the areal movements only, then the experimental set up (benchmarks, level, rods) may be considered as transparent and forgotten by the geophysicist. A true local invariant is obtained, which is very easy to interpret and is extremely useful for the volcanologist, as soon as the technical work has been properly made.

Of course with just two benchmarks we cannot observe the complete tilt, but only the component along the line formed by their alignment. In order to get the complete bi-dimensional tilt value, one must extend the process to a minimum of three non-aligned benchmarks. All the assumptions we had to bear previously are still necessary, the only difference is that the computation of the tilt angle TA is more complicated.

Let us assume the benchmarks are called A, B, C. We shall take A for the reference, but it does not matter as in fact any of the points may be used as a reference. This reference is a provisional one, used only in the processing of data, just to get easier the presentation.

At the date T1 we measure DNab1, the denivellation between A and B, and DNac1; at the date T2, we get DNab2 and DNac2. The distance A-B is called Dab, the azimuth angle between the North and the direction A-B is called AZab. In the same way, we have Dac and AZac.

We are now considering the horizontal plane P1 containing A and rigidly linked to the ground medium where A, B and C are fixed. It means that the relative positions of A, B, C and the plane P1 will not change whatever is the ground movement. The bidimensional tilt angle TA which has two components TAn along the North and TAe along the East has in fact this signification:

* The vector N1 (0 , 0 , 1) is normal to the plane P1 at the date T1, as it is horizontal at this period.

* At the date T2, the plane P1 has tilted.

The vector $\overrightarrow{N2}$ (TAe , TAn , 1) is a vector normal to the new position of P1, say P2. The same rotation that transforms P1 into P2 transforms N1 into N2.

With the values of DNab2-DNab1 and DNac2-DNac1 we can now easily find the equation of the plane P2.

The vertical line including B cuts P1 in B1 and P2 in B2. Idem for C, with C1 and C2. The plane P1 is defined by the three points A, B1 and C1, and the plane P2 by A, B2 and C2. This allows us to compute $\overrightarrow{N2}$, as in fact:

$$\overrightarrow{N2} = (\overrightarrow{AB2} \wedge \overrightarrow{AC2}) / \mathrm{Norm} (\overrightarrow{AB2} \wedge \overrightarrow{AC2})$$

And with the corresponding formula for N1, it is easy to find again the aforementioned coordinates, as AB1 and AC1 are in the z=0 plane (plane P1).

So, as:

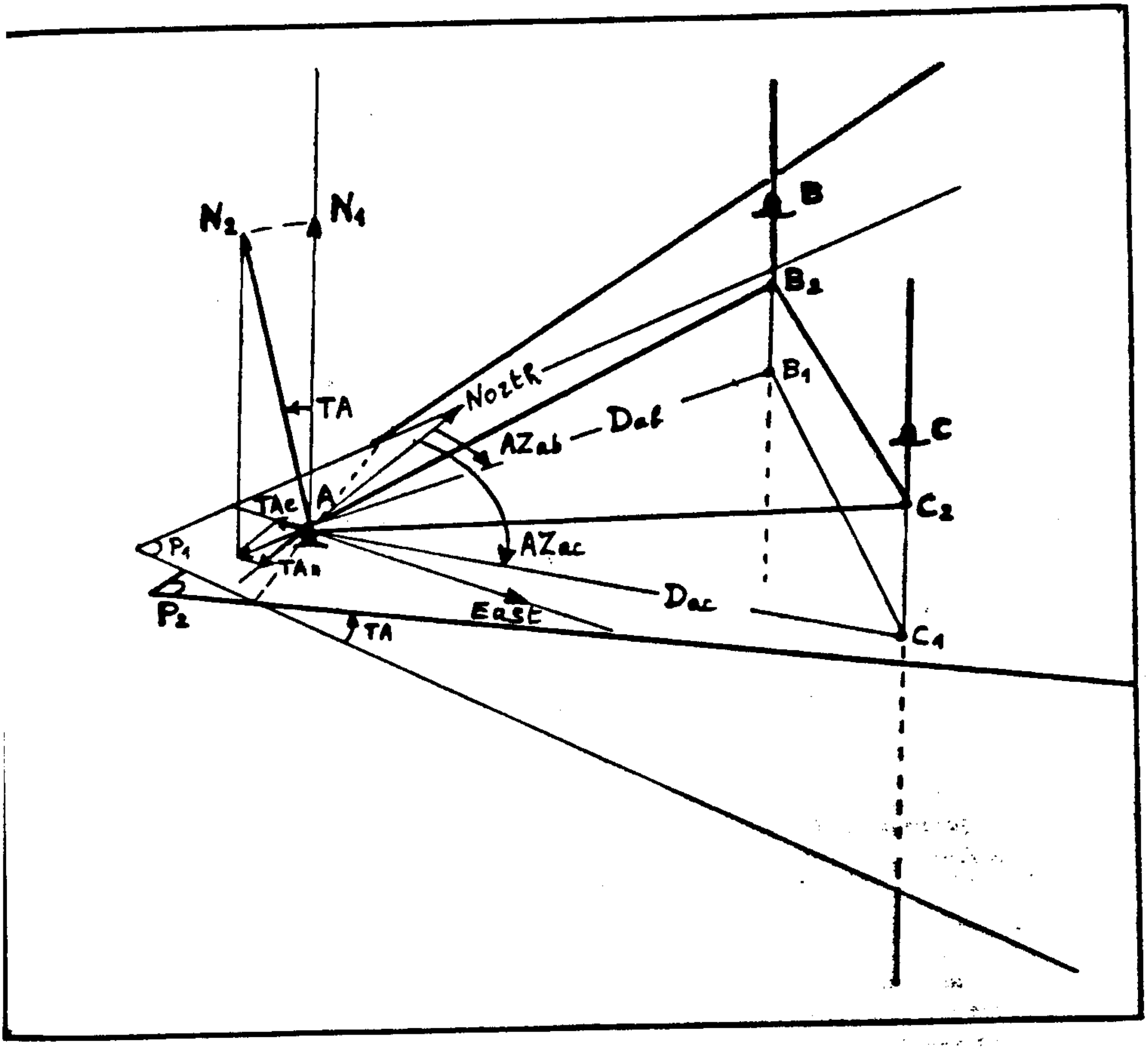
$$A \left| \begin{array}{l} 0 \\ 0 \\ 0 \end{array} \right. \quad B2 \left| \begin{array}{l} \mathrm{Dab.sin(AZab)} \\ \mathrm{Dab.cos(AZab)} \\ \mathrm{DNab2-DNab1} \end{array} \right. \quad C2 \left| \begin{array}{l} \mathrm{Dac.sin(AZac)} \\ \mathrm{Dac.cos(AZac)} \\ \mathrm{DNac2-DNac1} \end{array} \right.$$

Then,

$$\mathrm{AB2} \wedge \mathrm{AC2} \left\{ \begin{array}{l} \mathrm{Dab}.\cos(\mathrm{AZab}).(\mathrm{DNac2}-\mathrm{DNac1}) - \mathrm{Dac}.\cos(\mathrm{AZac}).(\mathrm{DNab2}-\mathrm{DNab1} \\ \mathrm{Dac}.\sin(\mathrm{AZac}).(\mathrm{DNab2}-\mathrm{DNab1}) - \mathrm{Dab}.\sin(\mathrm{AZab}).(\mathrm{DNac2}-\mathrm{DNac1} \\ \mathrm{Dab}.\mathrm{Dac}.\sin(\mathrm{AZab}-\mathrm{AZac}) \end{array} \right.$$

So that,

$$\boxed{\begin{array}{l} \mathrm{TAe} = \dfrac{\mathrm{Dab}.\cos(\mathrm{AZab}).(\mathrm{DNac2}-\mathrm{DNac1}) - \mathrm{Dac}.\cos(\mathrm{AZac}).(\mathrm{DNab2}-\mathrm{DNab1})}{\mathrm{Dab}.\mathrm{Dac}.\sin(\mathrm{AZab}-\mathrm{AZac})} \\[2ex] \mathrm{TAn} = \dfrac{\mathrm{Dac}.\sin(\mathrm{AZac}).(\mathrm{DNab2}-\mathrm{DNab1}) - \mathrm{Dab}.\sin(\mathrm{AZab}).(\mathrm{DNac2}-\mathrm{DNac1})}{\mathrm{Dab}.\mathrm{Dac}.\sin(\mathrm{AZab}-\mathrm{AZac})} \end{array}}$$


N2
N1
TA
B
B2
B1
C
C2
C1
North
AZab
Dab
TAc
A
P1
TAb
AZac
Dac
East
TA
P2

Once we have these values of the components of the tilt angle TA, we may compute the a of the tilt AZT and the value VT of the tilt by:

$$AZT = \mathrm{Arctg}\ (TAe / TAn) + (180 \text{ degrees} \quad \text{if } TAe<0)$$

$$VT = \sqrt{TAe^2 + TAn^2}$$

III/ EVALUATION OF THE PRECISION. ERRORS

Once we have seen how to get the results for a perfect theoretical process, we have to take in account all the practical imperfections of the physical methodology. We are going to list them, with an evaluation of the corresponding errors and the classical ways to minimize them.

a/Level

The high precision levels provided nowadays by topographic instruments factories are excellent and allow commonly to measure 0.02 mm on each rod. This accuracy is generally somewhat better than the true precision, except on a few instruments (WILD N3, WILD NA2, ZEISS NI1, ZEISS-JENA NI002 e.g.). Now the automatic levels allow to reach the same precision as the manual ones, and the best present-time level for volcanology seems to be the WILD NA2, with a parallel-plate micrometer. Its precision is around 0.02 mm, the line of sight may differ from the horizontal within 2", equivalent of 0.1 mm by meter of difference of distance between the rods. So to be consistent with the readings, the optimum is reached when the discrepancy between forward and backward rods distances do not exceed 20 cm. Another feature which is very important is the stability of the tripod during the observations. We shall discuss that when speaking about the procedures of observations.

b/ Rods

The best invar rods are not free of errors. The errors of graduation are now at an acceptable level on nearly all reasonably recent invar rods. But one must check carefully that no mark of impact on the invar plate is visible, because such a feature would change considerably the graduation errors of the rod. The verticality of the rod must be checked too. A very convenient way to verify the proper adjustment of the rods circular levels consists in a set up of the two rods at a few centimeters distant standpoints and to observe visually whether they are parallel or not. The acceptable dicrepancy between the base and top rod distances is around 1 cm. Another possible verification is to observe the rods, face and profile, with the level instrument properly set up, and to check the aspect of the rod against the vertical wire of the optics, which is generally quite well adjusted in the factory and will not need any further adjustment during the lifetime of the level. For the specific topics of dry-tilt, the best theoretical solution is to observe with only one rod, always the same, and at the same height of the level instrument over the ground. This is recommended if the rod is suspect (shocks for example).

When one uses two rods, it is important to test whether the origin of graduation is at the same place for them with reference to the base of the rod. The measurement is very easy: for a given position of the level, one has to get the readings on the two rods occupying successively the same standpoint. If the discrepancy between the readings after the closure (rod1 - rod2 - rod1) is below 0.03 mm, it means that it is possible to observe with the two rods regardless of their order. If not, it is preferable to measure with just one rod.

Something else which have to be checked is the flatness of the rod base. Here also the measurement is fairly easy: for a given position of the level,one must observe each rod when correctly set up on a good standpoint for different locations of the contact between the standpoint and the base plate. If a discrepancy of more than 0.03 mm is observed, a special attention must be paid to the position of the contact between the rods and the benchmarks or the intermediate standpoints. In any case, the rod-holder has to be very careful with the baseplate of the rod: no direct contact with the ground, if necessary the rod must lean on the top of the shoe of the rod-holder; avoid any dirt on the benchmarks before letting the rod repose on it.

c/ Problems of refraction

The so-called "refraction" is a very interesting natural phenomenon of atmospheric optics. A rough way to analyze it is to admit that the atmospheric pressure and temperature depend only of the altitude, so that the index of refraction, which expresses the speed of the light, has a gradient that is fairly vertical. An optical ray is therefore deflected, sometimes strongly, but always in the vertical plane. For this reason the measurement of horizontal angles with a theodolite may be, even at long distances, extremely accurate, but vertical angles are generally of a poor interest to get high precision denivellation measurements (except in the very specific case of trigonometric levelling with 2-theodolites simultaneous observations, but it is somewhat different, cf.I-4). For long distances, in geodetic networks for example where the line of sight is generally far from the ground, a rough estimate of the deflection of the ray is given by the empiric formula:

$$\text{Vertical deviation (meters)} = (\text{Distance in Km})^2 / 15$$

For short lines of sight, 30 meters for example, it would give a value of 0.07 mm. But for the direct levelling, it is often much stronger, about ten times more, because in the first meters the vertical index gradients are very important; so that the deflection of the line of sight may reach in such a case a value of around 1 mm, and approximately proportional to the square of the distance involved. This first analysis could let us think that when the two distances backward and forward are equal, the two deviations which are also equal cancel each other. But this is generally not the case, except when the meteorological conditions are good (no sun, some wind, all conditions where thermal exchanges are small), or when the positions of the ray paths above the ground are quite similar (flat areas, same exposition to the sun).

We must remember that a strong difference exists between the refraction itself, generally difficult to observe, and the thermal deformations of the image that leads to difficulties in aiming at a target because it seems to move all the time. When the short-term stability of the image is good, it may be a very bad period for observing if the refraction changes slightly and regularly, as within a time of a few minutes the reading will change of several 0.1 mm (sunrise and sunset e.g.). On the opposite, when the thermal agitation is strong one may do good measurements, despite the difficulty of observation, because the mean value of the reading will not change at all within half an hour (at noon e.g.).

In conclusion it easy to see that such errors are extremely difficult to forecast, as they depend merely of the meteorological parameters, which are almost impossible to model correctly. All the quality of the data finally depends on the skillfulness of the field observer.

d/ Quality of benchmarks set-up

Another important possible source of loss of precision is the benchmarks set-up. As it was said previously,the benchmark is a sampling of the ground medium and it is not allowed to move alone. It should be emphasized that the results from dry tilt stations may be extremely poor even for instabilities of the benchmark that anyone would have accepted for a levelling network, and that the benchmarks have to be built with extreme care if we want to be homogeneous with the other sources of errors.

e/ Conclusion

When all the experimental items already listed have been properly optimized, it is possible to reach a precision of nearly 0.02 mm. At a distance of 40 meters between the marks it allows to reach a precision of better than 1 microradian, which is generally accurate enough to monitor even very modest volcanic deformations with an acceptable signal/noise ratio.

IV/ ENHANCED DRY TILT STATIONS

a/ Introduction

For all the reasons previously mentioned, we must notice that it is somewhat difficult to appreciate the true errors on the tilt angle, as it depends of a lot of parameters among which are the very variable meteorological conditions. We have seen that it is easy to compute the tilt angle, but we have no objective way to evaluate correctly the precision. So we have to correct that, and the improvement we are looking for is a solution allowing us to determine the confidence level of the result. Therefore we cannot conserve dry tilt stations with just three benchmarks. We will consider solutions using a minimum of four benchmarks, or even more.

The way to evaluate the a-posteriori errors on results is very simple for topographic methods. We have just to provide a number of independent observations higher than the number of unknowns to be found. All the data in excess contribute, via the geometric model of the topographic figure used, to appreciate the errors on the result. The more classical way to do is to use a least-squares adjustment of the raw observations. For the case of dry tilt, this leads to do the following:

* With N benchmarks we can draw N-2 independent triangles. Of course we must find geometrical configurations for which the different triangles have nearly the same shape.

* For all of these triangles, we must compute the tilt angle TA as it was previously shown.

* Then we have to compare the results. If the various triangles are similar in shape, the mean and the standard deviation of the TAs (i.e. of the components) gives the best estimation for TA and its confidence level.

It is easy to see that 4 benchmarks is just a minimum, and that a good station may use 6 or even more, for example when the set up conditions are poor. With 4, we just have a rough estimate of the errors. With 5 or more, if one of the benchmarks suffers from a shock, we can point out which one is faulty. With just 4, we cannot.

The best way to draw an Enhanced Dry Tilt Station is to set up all the benchmarks on a unique circle, with a radius between 15 and 30 meters for example, with a mark in the center (or better, a pillar) where to put the level so that all the distances of observation are nearly equal. The size of the circle depends of the flatness of the area, of the general meteorological conditions (shades of trees or sun exposed zones). The data processing should be done immediately in the field, with a programmable pocket calculator or a small computer if any available. It is quite advisable to store the observations on a diskette for further processing and to have a paper print of all readings as a multipurpose back-up.

b/ Observation procedure

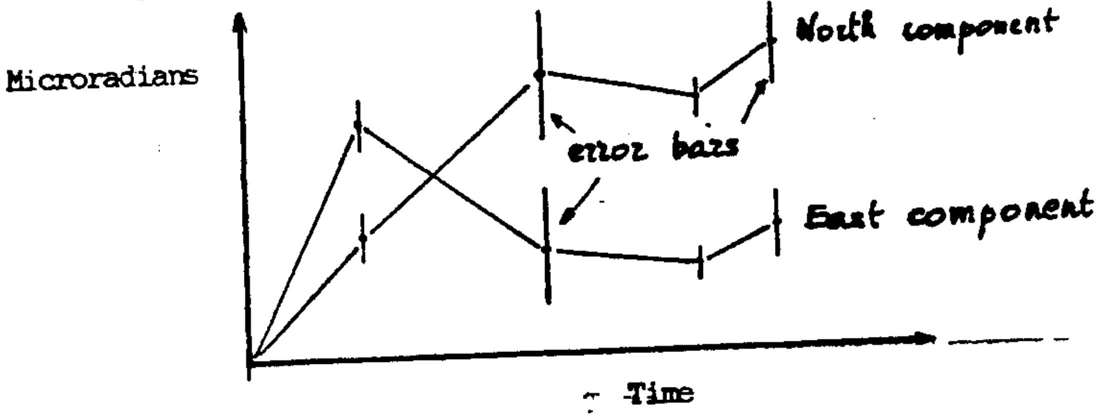
First the level must be set up on his tripod, so as to allow it to stabilize within a few minutes. If possible a protection against the sun is advisable, although it is not absolutely necessary with modern instruments. If the rods have no appreciable origin discrepancy (cf. III,b "Rods"), the two invar rods will be used. One of the benchmarks, called A for example, will be the reference, so that it has to be observed first. For every rod station two readings are made, one on each graduation of the rod. After the last benchmark is surveyed, a new observation is done in A again. This "closure" gives only a check whether the level+tripod system has been stable during the few minutes of measurements since the beginning. If it is too high (e.g. over 0.1 or 0.2 mm), it may also mean that the refraction is presently in evolution. In this case a new set of measurements must be done. One must be aware that the misclosure is unable by itself to give an evaluation of the quality of the result. Only when it is big we get a sort of warning that something is wrong with the tripod, the level or the refraction.

The misclosure must be compensated by its regular repartition over all the readings. Then the data processing must be made, so that a standard deviation for all triangles is obtained. Then one has to choose either to repeat all the measurements if the quality seems poor, or to stop for this station.

V/ REPRESENTATION OF THE RESULTS

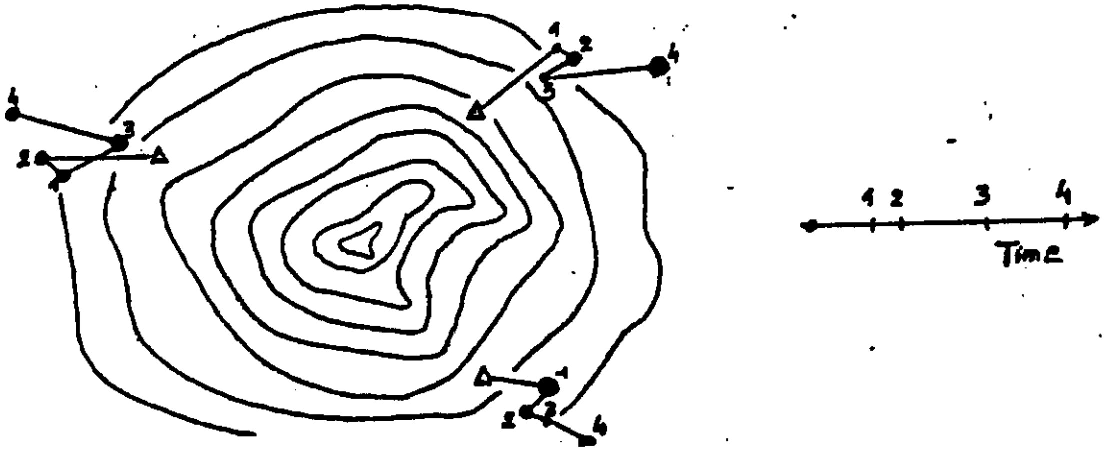
An important aspect of the surveyor's work is to choose a suitable display of the results. We must remember that the most efficient way to input some data into our brain is the visual one, as anyone has extremely powerful means to preprocess data in his vision system. When we have dry-tilt results, we get always a tridimensional set of informations (2 components of tilt angle and one of time) so that we have obviously one in excess for a paper illustration. And, as we do for any sort of map, we have to choose a representation among various possible ones. The prospects we get are the following ones:

* Two drawings of one component of the tilt angle versus time. All the available informations are shown, but the immediate reading is difficult. And if we have many different stations, it is impossible to understand at a glance the behavior of the complete network. But we have no problem to represent simultaneously the movements and the errors, so that it is easy to appreciate their level of significance.

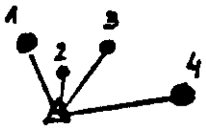


* One drawing of the tilt angle, displayed as one point (identified by a number) for each date of measurement. Two consecutive points are linked by a line. In the figure captions we have to give the dates corresponding to each number, possibly with another separate drawing. Thus we display the hodograph of the extremity of the vector (N in the paragraph III) at different epochs, that is to say its successive positions, given by the points whose coordinates are the successive values of TAe and TAn when referenced to the same initial situation. Simultaneously we may display the errors by drawing a circle (whose

radius is the variance of the various simultaneous determinations of TA) around each point. The faulty aspect of this representation is easy to point out if the remeasurements have not at all been regularly performed. The reader may unconsciously understand that the successive points of the graph correspond to regularly spaced epochs of measurements. But a great advantage of such a representation is that we may compare simultaneously the patterns of several dry tilt stations, and another one is that we see the movements directly, without any complementary model to use in order to ease the reading.



* Display with radial lines from a central point of the variations of tilt between two successive dates. That way it is also possible to show the movements of many stations simultaneously, but we cannot easily understand the integrated movement over long time periods.



From these three technical solutions we prefer the second one, which in many cases and especially on volcanoes proves to be quite convenient.

VI/ CONCLUSIONS

The "dry tilt" methodology is a simple way to monitor the ground tilt, but we must be aware that a lot of precautions have to be taken whenever we plan to achieve the maximal precision. It is possible to get precision below 1 microradian, but let us remember that it implies to master a lot of phenomenons of an amplitude around 0.01 mm, or 10 micrometers, and that nobody has any sensible experience of such small things. At this level of precision, nothing is rigid, everything is deformable, for example the ground under our weight. So the most important features to get good results are to develop among surveyors a high degree of technical skillfulness and a good conscience of the physical problems that happen in the field when they look for very high precision.

ANNEX II

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USE OF TENSORS AS AN HELP TO DISPLAY DEFORMATIONS IN A NETWORK.

Use of Monte-Carlo methods to display errors on deformation tensors.

I. INTRODUCTION

When we have two sets of observations on a given geodetic network, we experience a very classical problem of interpretation if we try to compare them in order to get informations concerning the deformations that occurred between the two epochs. The main difficulties are:

- To display the movements without need of a preliminary model whose inadequation may hide the results.
- To display in a correct physical way the confidence level of the results.

A common approach has been to use displacement vectors to show the movements in the network. Since a long time it has been pointed out that this solution could lead to important misunderstandings, as it needs a preliminary assumption of stability of one point and one direction in order to allow the computation. So another method have been used, it uses in each basic figure of the network (i.e. generally triangles) the calculation of the strain tensor which, applied to an infinite bi-dimensional homogeneous medium, will provoke the same deformation pattern as the one observed. The tensor is represented by its two main axes, with arrows at the center of each basic figure. The strong interest of this display is that it needs no preliminary hypothesis, no assumption of stability. It is an intrinsic display. On another point of view, it is not as easy to read as displacement vectors for most people, and a small training is advisable for a correct understanding of such drawings. But it is basically the best possible solution to analyze quickly even a large network in order to detect non deformed parts and areas where maximum movements occur.

Anyway a new problem arises, that is how to display the errors on the tensors in a convenient way. For a long time a large use has been made of eventails around each arrow, but this method which is approximately correct for a good signal to noise ratio is actually false for small movements because the conditions of the calculus become completely non-linear so that the mathematical base is quite wrong.

We propose here a solution to overcome this difficulty using Monte-Carlo methods, as it is commonly used when a statistical problem proves to be highly non-linear.

II.DATA PROCESSING

II.1.Least-squares adjustments of the different sets of data

The first operation to be done once the field data have been properly checked and corrected (e.g. meteorological corrections for EDM) is to compensate separately the sets of data with the same approximate initial coordinates. A special attention must be paid to the weights attributed to different observations, as we must remember that a large difference of weight between data will in some way impose the best, and nearly forget the worst ones. This is an opportunity to notice that when we mix observations got with different techniques, if the quality level is not rather similar, only the best ones will prove to be useful. For example if we observe a large geodetic network with laser EDM and triangulation, in nearly all the cases the result will not take in account the angles but only the distances (that may be up to 5 times better in most situations).

Once we have got the data adjustments, we must carefully notice what are the a-posteriori variance of the observations. These values have a real statistical meaning only if the redundancy is not too small, and we must keep them for further processings. Even if this so-called precision is just a statistical notion, somewhat different from the physical characterization of errors, because the least-squares adjustment requires many statistical assumptions that are generally false (e.g. Gaussian normal model of errors), we must use it as we have no other solution.

II.2.Use of tensorial display

Let us suppose that we work with two sets of data at epochs T1 and T2. We will now decompose the network in a series of triangles, in a somewhat arbitrary way of course but it does not matter. For each triangle we have the two sets of coordinates for T1 and T2. We compute the strain tensor according to the following:

The coordinates of points A, B, C at epoch T1 are given as :

A1 (xa1, ya1) , B1 (xb1, yb1) , C1 (xc1, yc1)

and at epoch T2, as :

A2 (xa2, ya2) , B2 (xb2, yb2) , C2 (xc2, yc2)

We call U and V the components of the displacement vectors, so that we have:

$$Ua = xa2 - xa1 \;,\; Va = ya2 - ya1$$
$$Ub = xb2 - xb1 \;,\; Vb = yb2 - yb1$$
$$Uc = xc2 - xc1 \;,\; Vc = yc2 - yc1$$

We assume that the displacements are correlated linearly with the coordinates, so that:

$$Ui = a.xi + b.yi + c$$
$$Vi = a'.xi + b'.yi + c'$$

Now we write the 6 equations like these two ones for the three points A, B and C, and we get the values of a, a', b, b' (c and c' are useless for us):

$$a = \frac{(\, yc1 - ya1 \,).(\, Ub - Ua \,) - (\, yb1 - ya1 \,).(\, Uc - Ua \,)}{(\, xb1 - xa1 \,).(\, yc1 - ya1 \,) - (\, xc1 - xa1 \,).(\, yb1 - ya1 \,)}$$

$$b = \frac{(\, xb1 - xa1 \,).(\, Uc - Ua \,) - (\, xc1 - xa1 \,).(\, Ub - Ua \,)}{(\, xb1 - xa1 \,).(\, yc1 - ya1 \,) - (\, xc1 - xa1 \,).(\, yb1 - ya1 \,)}$$

$$a' = \frac{(\, yc1 - ya1 \,).(\, Vb - Va \,) - (\, yb1 - ya1 \,).(\, Vc - Va \,)}{(\, xb1 - xa1 \,).(\, yc1 - ya1 \,) - (\, xc1 - xa1 \,).(\, yb1 - ya1 \,)}$$

$$b' = \frac{(\, xb1 - xa1 \,).(\, Uc - Ua \,) - (\, xc1 - xa1 \,).(\, Ub - Ua \,)}{(\, xb1 - xa1 \,).(\, yc1 - ya1 \,) - (\, xc1 - xa1 \,).(\, yb1 - ya1 \,)}$$

We compute the principal strains PS1 and PS2 with the formula:

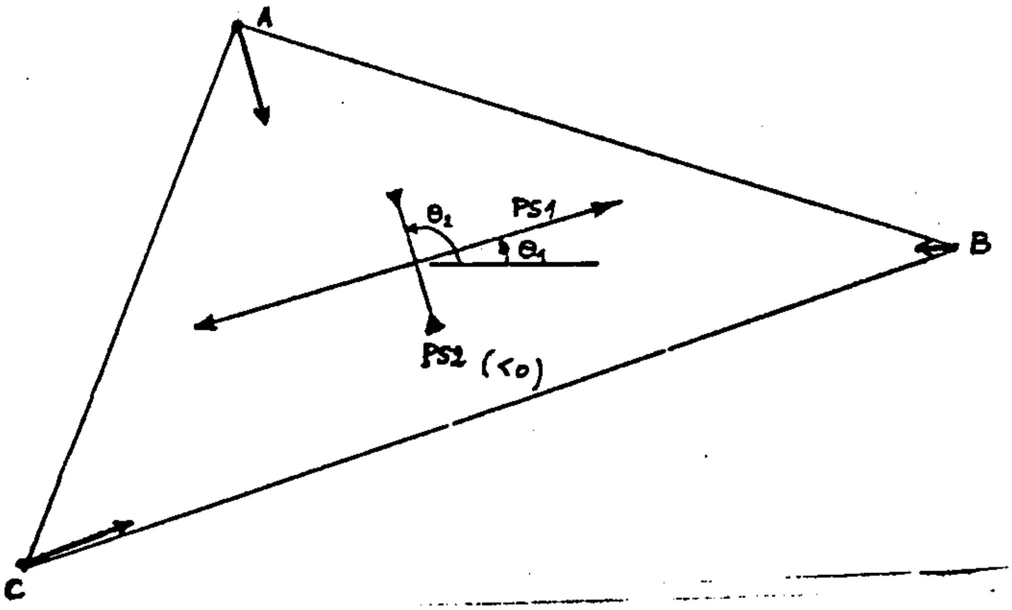
$$\text{PS1 and PS2} = \frac{a + b' \pm \sqrt{(a - b')^2 + (a' + b)^2}}{2}$$

And the orientations of these principal strains are given by:

$$\text{Tan}(\theta 1) \text{ and Tan}(\theta 2) = \frac{b' - a \pm \sqrt{(a - b')^2 + (a' + b)^2}}{b + a'}$$

The strain tensors will be represented by arrows going outwards if PS1 (or PS2) is positive (extension), and inwards if negative (compressional strain).

Then we may display with these arrows one strain tensor in each triangle.



II.3.Display of errors on strain tensors. Use of a Monte-Carlo method

A this step of the work we are going to use the good possibilities of computation that we have now easily.

From the initial least-squares adjustments we have got for each epoch one set of compensated values with their standard deviation. Now we are going to synthesize a large number of other sets of artificial observations, for example one hundred for each epoch, obeying a normal law with the aforementioned standard deviation (Monte-Carlo method: we will see later how to compute these synthesized data). Then we take one set of data for each epoch, we do again the adjustments and compute the strain tensors. Then we take a new set and compute the strain, and so on, for one hundred times in this example. For each triangle we have now one hundred tensors, and we just have to display the mean values with arrows, and the extremity of the arrows for each computation will be represented by a point. The final result is the set of four arrows surrounded by clusters, for every basic triangle we have chosen. Such a representation is very convenient as it allows to see directly if a given tensor is significant or not. We may now observe at a glance which parts of the network behaved as rigid ensembles with respect to the precision of the measurements.

II.4.Final representation

If the people that will interpret the results are familiar with the strain tensors, we may choose to stop there. If we want that the results will be understood by everyone, it is convenient to use also the displacement vectors display. But as we have already the best means to understand correctly the behavior of the area, we will choose without any risks of mistakes the "fixed" point and direction in a stable area. The vectors will represent the movements of one part of the network with respect to another one, and we have no artificial spurious deformations superimposed on them. But with such a method we have no good solution to display simultaneously the errors. The classical error ellipses are easy to compute, but they have a very specific physical meaning which proves to be generally useless for the user. These ellipses show the errors for a displacement vector with respect to the "fixed" point. Thus we have only the errors on relative movements between any point and the "fixed" one, and no information is displayed concerning the significance level of any other relative movement in the network. It means that these ellipses are consequences of the errors of measurements and also of the choice of the references. They are in no way an help towards an intrinsic analysis of the results.

A final remark will be done concerning the very convenient use that we can do of the strain tensors when processing triangulation data, especially for comparisons with old observations. In these cases, the scale of the figure is often poor, it means that the results are homothetic of the true values, but we do not know the homothety factor. In such a situation, every elementary figure will display a parasitic supplementary isotropic tensor, even in stable zones, quite easy to detect because it is not a common physical behavior of the earth crust on large scales. And it is not difficult to remove visually an isotropic tensor from a display if necessary. So this tensorial representation is very suitable and even necessary to process these types of angular data.

III. EXAMPLES OF RESULTS

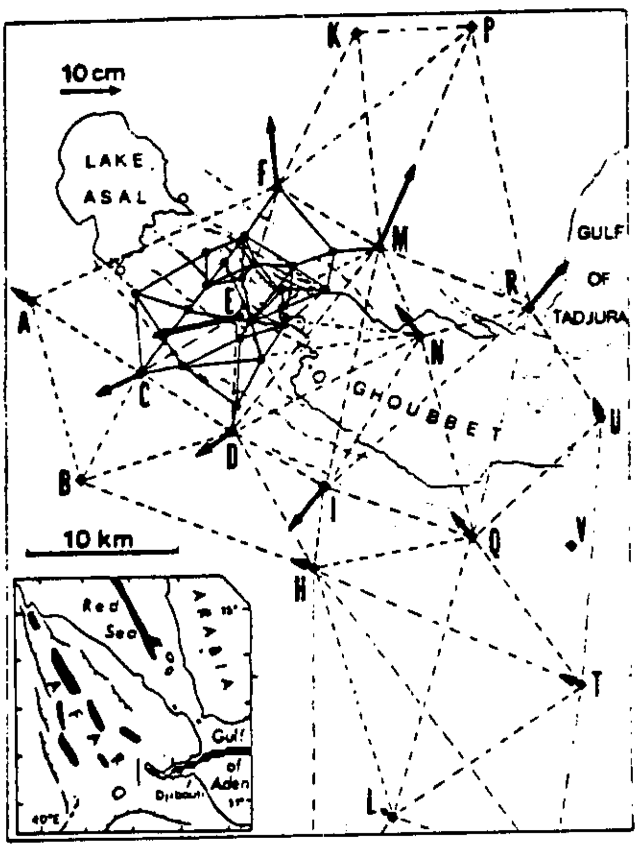


Fig.1. Geodetic networks across the Asal-Ghoubbet Rift, Djibouti. Rhombs indicates the stations of the large aperture network (1973-1979-1984) and filled circles those of the intra-rift trilateration network (origine 1979). In inset the geodynamical environment. Arrows denote the displacement vectors issued from the 1984-1979 comparison, taking station B and BT direction fixed.

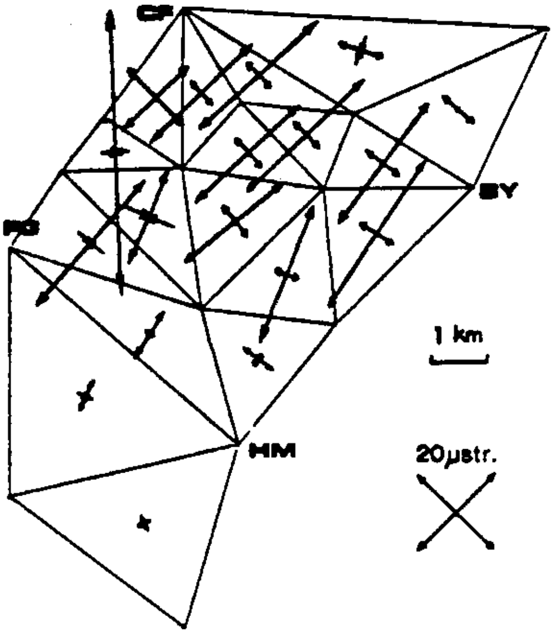


Fig.4. Principal components and directions of the strain tensors for selected triangles of the intra-rift network.

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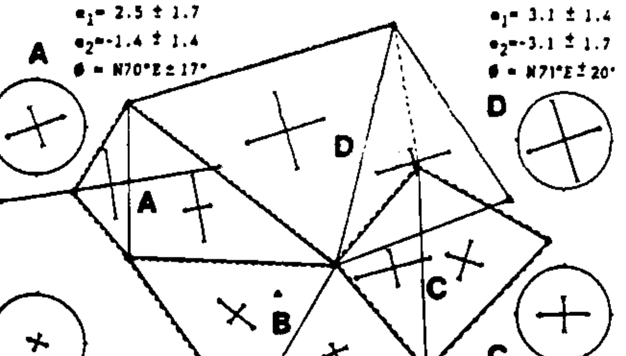

gure 4. Strain tensors for selected triangles of the net-
rk. In the circles, mean strain tensors for the four subre-
ions delimited by dashed lines, and principal values of
tension and contraction axis, and orientation of the exten-
ion axis.

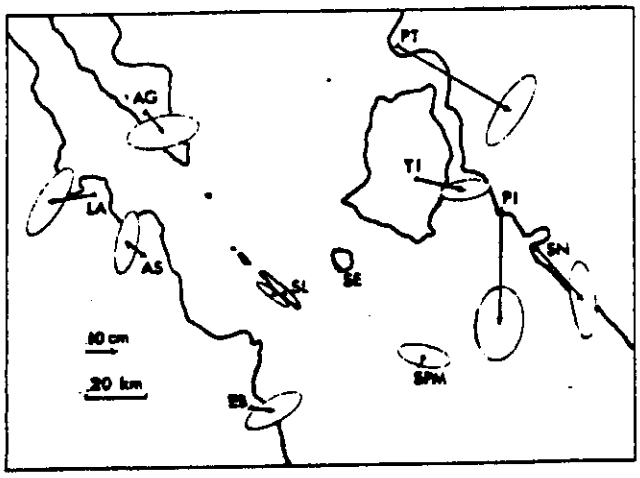

Figure 2. Displacement vectors obtained by fixing station SE and azimuth SE-AG, with associated error ellipses corresponding to 1 standard deviation.

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IV. APPENDIX: Synthesis of data obeying a given normal law

Let us suppose that we want to synthesize a set of distances in an artificial way, knowing the mean value Dm and the standard deviation S of one distance (such informations have been given by the preliminary adjustment in our case). We suppose just that we dispose of the RANDOMIZE function in our computer, able to provide with equal probability any value between 0 and 1. An easy way to have a correct gaussian variable of a given standard deviation S is to get 8 random values (between 0 and 1), to take their mean, to substract 0.5 and to multiplicate the result by 10 x S .

So, a distance D obeying the law will be given (in rough way, of course), by:

$$D = ((\text{Sum of 8 random values})/ 8 - 0.5) \cdot 10 \cdot S + Dm$$

ANNEX III

CALIBRATION OF AN ELECTRONIC DISTANCE MEASURING (EDM) INSTRUMENT

I. INTRODUCTION

A proper calibration of an EDM instrument should be done every year at least, because of various types of drifts experienced by the electronic and mechanical parts of these devices. It has also to be performed every time that we use different reflectors. Any EDM may work with any equivalent quality prism, regardless of its origin, but a new calibration is then necessary.

II. MODEL OF ERRORS FOR EDMs

In order to understand how to operate, it is necessary to know the types of instrumental errors of EDMs. They may be divided into three groups:

- An error proportional to the measured distance, due to the drift of the internal frequency standard. If the actual frequency is F1 and its theoretical value F2, the error on a distance D is given by:

$$D \cdot (F1 - F2) / F1$$

This error is often negligible on short distances and in most instruments should be around 1 ppm. The only way to check it is by a frequency measurement using a high-quality frequency standard.

- An error displaying a cyclic behavior, often due to insulation problems, and thus taking the same value at distances differing from one half wavelength of the modulation frequency. This error is small (less than 1 cm except on old instruments).
- A constant error, corresponding to the physical position of the origin of the EDM compared to the mechanical centering. This is the principal one to be checked.

III.CALIBRATION

A very simple and convenient way to get the calibration is the following:

- We must set up a minimum of 3 tripods with a forced centering system, for example the WILD tribrach's one. These tripods must be carefully aligned in azimuth and site on a flat area. The distances between them should be of a few tens of meters, with a preference for an exact multiple of 10 meters, as most of the EDM use a frequency of 15 MHz. That way we do not mix a possible cyclic error with the constant one, and the ranges are so short that the proportional error is negligible.
- Let us assume that we have 3 stations A, B and C. If the constant error is c, AB being the true value of distance between A and B, and ABm being the measured value, we may measure AB, BC and AC, so that:

$$ABm = AB + c$$
$$BCm = BC + c$$
$$ACm = AC + c$$

And, as AB + BC - AC = 0 by definition, we find out that:

$$c = ABm + BCm - ACm$$

So that we determine c without any data concerning the exact position of the tripods, for example we do not need in any way a known baseline.

- Of course with 3 points we have just the minimum information to determine c. It is highly advisable to get a check about this value, so it is better to get extra determinations. A convenient solution is to use 4 points, so that we get 3 independent determinations of c.

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