A NEW "ELECTRODELESS" RESONATOR DESIGN +

Raymond J. BESSON

Ecole Nationale Supérieure de Chronométrie et de Micromécanique
La Bouloie - Route de Gray
25030 BESANCON CEDEX, FRANCE

Summary

In a recent paper, new structures, all using uncoated crystals, have been out-lined (and called B.V.A.$_n$ designs).

The main purpose of this paper is to give a complete description of the B.V.A.$_2$ design. In this design, the active part of the crystal is connected to the dormant part by little quartz "bridges", which can be very precisely made and located. As the fixation is made out of quartz, there is no ordinary bonding and among the consequences no discontinuity is caused by the fixation. Also, it is possible to avoid the stresses which could be caused by the machining of the quartz "bridges". Since the electrodes are located on insulators very close to the active surface of the wafer, the frequency of the device can be easily adjusted by means of a serie capacitance. Nevertheless, the construction of the device allows a very accurate frequency adjustement. As consequences of the construction acoustic losses are extremely low, a very high Q factor is obtained and the short term and long term stabilities are improved.

The first part of the paper deals with the construction parameters (wafer evaluation, excitation conditions and resonator mounting). Especially, the shape, dimensions and location of the quartz "bridges" are studied. The influence of the gap is discussed.

In the second part of the paper, resonators constructed according to the design are studied by various techniques. Acceleration effects are discussed. For comparison purposes, numerical data concerning AT 5 MHz fifth overtone units are given (electrical parameters, frequency spectrum, stabilities, amplitude frequency effect,...). Nevertheless, some results concerning other frequencies and S.C. cuts are also given. The problem of industrial fabrication is quickly discussed.

As a conclusion, the various results are reviewed and discussed (from the fundamental and technical points of view as well).

Key Words : Piezoelectric Resonator, Quartz Unplated Crystals, Electrode Effects, Bonding Effects, Frequency Stablility, Aging, Frequency Adjusting, Crystal's Noise Reduction.

Introduction

In a recent paper [1], we pointed out that mastering the boundary phenomena could reduce the aging and crystal's noise contribution as well. New structures, all using uncoated crystals, were outlined and called B.V.A.$_n$ designs :

- if n is odd, a rather conventional bonding and a special fixation is used. (In the B.V.A.$_1$ type, described last year, the main feature is that the crystal is "electrodeless" and frequency modulable).

- if n is even, the design uses improved bonding and mounting.

This denomination indicates two successive steps of our attempt to reduce the crystal's noise and frequency drift contribution.

Since the B.V.A.$_3$ design is an improvement of the B.V.A.$_1$ design it will be very rapidly described using the scheme of Fig.1. The vibrating quartz crystal C of a given cut, orientation, geometrical shape (in Fig.1 a planoconvex disk) is, for instance, TC bonded (3 or even 4 bonding points ref.T) to the lower disk D_1 (which has been given a curvature identical to the curvature of the wafer's lower surface). D_1 is usually made out ot quartz of the same cut and orientation. The electrodes are evaporated on the lower disk D_1 and the upper disk D_{21} or D_{22}. The upper disk is not necessarily made out of quartz and may have any radius of curvature. The intermediate ring R determines the upper gap giving access to frequency adjustement or modulation. Compared to B.V.A$_1$ type this design has mainly the same properties but the characteristic features are greatly improved in severe environmental conditions.

B.V.A.$_2$ RESONATORS

Special emphasis is given to this design which overcomes some difficult problems caused by the conventional evaluation of piezoelectric resonators. We mainly describe here quartz material 5 MHz units but, of course, other piezoelectric materials can be used and resonators of various frequencies have been evaluated.

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1 - Introduction and general description :+

Our goal was to obtain an "electrodeless" resonator (so as to overcome the difficulties due to electrode deposition) with a fixation exhibiting neither discontinuity nor local stress in the fixation areas. We wanted to obtain a device the frequency of which could easily be adjusted by means of a series capacitance. Then a large gap capacitance is suitable i.e. electrodes have to be located very close to the active surface of the wafer (in the micron range or even the 10 microns range). Also, and this is very important too, we planned to obtain fixation areas very accurately located and fixation means precisely known.

The B.V.A.$_2$ resonator is represented by the schemes of Fig.2 - Fig.3 - Fig.3a - Fig.6 and Fig.7 and the pictures of Fig.4 and Fig.5. It includes :

- a vibrating quartz crystal, ref.C, the surface of which has been very carefully prepared. The active part of the crystal is connected to the dormant part by little quartz "bridges" very precisely made and located.
- a quartz condenser made of two disks (ref. D_1 and D_2) of the same cut and orientation on which the electrodes are deposited.
- means to maintain the condenser and crystal tighted together (it can be those recently described [1]).
- a metallic experimental enclosure which is sealed by a pinch off process (a special coldwelded type enclosure has been made but not tested yet).

It must be pointed out that some construction parameters, especially the support configuration parameters, can be, using this design, very precisely known. Also since the crystal is "electrodeless" and uses an all quartz structure it is very suitable for low temperature applications [2]. Moreover, the electrodes may be deposited on insulators which have been given a curvature different from the crystal surface's. This feature gives access to additional possibilities and may be used to modify Q factor, motionnal parameters series resistance and frequency amplitude effect.

Such a resonator, beeing entirely different from a conventional resonator, needs theoretical and technical studies specially devoted to it.

2 - Evaluation of the vibrating crystal :

The original part of this evaluation will only be described here. By use of ultrasonic machining and precise lapping [3] little bridges are left between the external dormant part of the crystal and the internal vibrating part. Those bridges have a given shape, a given thickness, a given lenght.
The schemes of Fig.6 outlines various possible shapes. The bridges can be very precisely located with respect to the thickness of the crystal (accuracy of the location : ± 10μ). Their angular position can also be very precisely known (± 0.04°). Of course, the technique has to be perfectly mastered (for instance, avoiding a conical ultrasonic machining is not immediate) but, with sufficient experience, the process can be considered as sure, rapid (2 or 3 minutes) and very accurate. As a consequence the middle part of the bridges can be located at the very nodes of vibration. Also, unwanted modes can be better eliminated. Since the thickness in the middle part ot the bridges has ranged from 50μ to 1200μ (the usual is approximately 200μ) the bridges are not especially brittle. Any number of bridges can be left. Especially one single bridge, covering 360° angulary, may be directly lapped so avoiding the ultrasonic machining (Fig.3 a).

It must be pointed out that the machining does not destroy the material from the cristallographic point of view as can be seen from Fig.8 (vibrating 5 MHz fifth overtone, SID or Lang topography).

Moreover, no additional stresses are left by the machining if the quartz wafer is subjected, prior to mounting, to annealing at about 480°C, followed by a very slight surface attack with bifluoride.

The lenght and thickness of the bridges have been theoretically [4] studied. Assuming a flexure vibration of the bridge, it is found that a length of 2 mm and a thickness of 0.2 mm is a good compromise between a weak static strain and a minimum acoustical energy transmission between the vibrating and dormant part of the crystal (5 MHz fifth overtone).

3 - Reflection of the elastic waves and influence of the gap :

The reflection of the elastic waves is not influenced by the position of the electrodes with regard to the crystal surface. It mainly depends on phenomena which occur in the boundary neighbourhood and which are due to crystalline modifications caused by machining processes and surface preparation.

The sample surface is carefully lapped and polished, so as to reduce the layer in which acoustic dissipation occurs. Defects due to machining processes are carefully investigated (X ray topography, electron microscopy and so on) so as to define the best procedures [6]. As far as possible, we operate in a clean room atmosphere, try to process the crystal in dry nitrogen and, of course, use the results of recent investigations for cleaning and decontamination [6].

The influence of the gap has been studied. Experimentally, the Q factor is not a constant versus the total gap [3]. The variation depends on the frequency and overtone number of the unit. Of course, the variation is not important (smaller than 10 p.cent for gap variations from 0 to 1 mm).
Nevertheless an investigation was started and proved that usual equivalent circuit is not sufficient [5].
So, starting from the exact expression of the current, we computed the Q factor versus the gap (assuming a plane infinite plate) and found a variation which gives a better account of the results.

Actually, a compromise must be choosen. The series resistance and the motionnal inductance strongly increase with the gap. Also, the frequency of the unit must be easily adjusted by a series capacitance ; so very thin gaps are suitable.

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But the mechanical stability of the gap thickness is to be considered too, if ultrastable units are desired. For a 5 MHz fifth overtone we use gaps in the micron or 10 microns range. Nevertheless for resonators on the fundamental mode the gap can be larger.

Usually, the gaps are made by a special lapping[3] process which affects the central area of D_1 and D_2 (see Fig.2). They can also be made by nickel electrodeposition as suggested by Fig.7. It must be pointed out that slightly different gaps can be made so giving access to very precise frequency adjustement (1 Hz for a 5 MHz fifth overtone unit).

Main Characteristics of B.V.A.$_2$ Resonators

As pointed out last year, B.V.A.$_2$ resonators are given more interest in the high frequency range since the electrode and bonding phenomena are relatively larger for high frequency crystals.
Nevertheless, for comparison purposes, numerical data concerning AT 5 MHz fifth overtone units are given.

1 - Electrical parameters :

Resonators evaluated with good natural quartz correspond to Q factor and series resistance given by :

$$Q \simeq 3\,10^6 \qquad R_1 \simeq 60\Omega$$

We are presently conducting an investigation covering the following types of material :

- Natural Quartz (various origins)
- Electronic Grade Quartz (various origins)
- Optical Grade Sawyer Quartz
- Premium Q Sawyer Quartz
- Premium Q Sawyer Swept Quartz.

2 - Stabilities :

The results concerning the short term stabilities have already been given[1] ; some improvements have been obtained but they are not significant.

Long term drift experiments have been carried out in our Laboratory (M. Decailliot and J. Chauvin). The reference is a Cesium beam standard. A Butler oscillator is used ; the level of oscillation, which is about 1µw, is regulated (approximately to 10^{-4}) and the temperature is stable to better than 10^{-3}°C over large periods of time. The signals are 10 times frequency divided ; then phase compared. The intervals of time between two phase coincidences are automatically recorded. Using B.V.A.$_2$ crystals, not pre-aged at all, the following drifts per day have been obtained :

- immediately : 2 to $2.5.10^{-10}$
- after a month continuous operation : 3.10^{-11}
- after two months continuous operation: 7.10^{-12} to 1.10^{-11}

The experiments are going on but the regular decrease of the drift is to be pointed out.

Nevertheless, this result must not be regarded as definitive as long as we don't use a coldwelded type enclosure. (in our experimental soldered enclosure the crystal is contaminated and it cannot be baked and pumped down at temperatures higher than the solder melting point).

3 - Static acceleration effects :

B.V.A.$_2$ resonators of various types (different support configuration, plano-convex or bi-convex units) have been studied and tested in the "Office National d'Etudes et de Recherches Aérospatiales" (ONERA) by M. Valdois and D. Janiaud.

The experiments performed are principaly related to the influence on the resonator frequency of the direction of an acceleration of constant modulus. Resonators have been tested either in passive networks or in an oscillator loop. Acceleration vectors in three orthogonal planes associated to the resonator are applied. Experimental results are similar to those obtained with customary 2 or 3 support units. All frequency deviations are sinusoïdal functions of azimuth angle (the zeros of these functions define null influence directions). Those 3 directions of null influence determined by studying the 3 associated planes, belong to a same plane which is called "accelerometric null influence plane"[7]. Thus, it is proved that a plane exists in which any acceleration has no measurable influence on the resonator frequency (the frequency variation $\frac{\Delta f}{f}$ is measured with a 10^{-11} accuracy). As a consequence the direction perpendicular to this plane is the maximum influence direction.

Mainly, the following B.V.A.$_2$ AT resonators have been tested :

- plano-convex resonator with a single 360° bridge. Maximal values of the sensitivity from 4.10^{-9}/g to 8.10^{-9}/g have been recorded. It must be pointed out that the symetry of the bridge with respect to the center of the resonator was not guaranteed by the machining.
- plano-convex four bridge resonator (bridges along Z Z' and X X'). Maximal sensitivities of $1.5.10^{-9}$/g to 2.10^{-9}/g have been recorded. (This is slightly less than values recorded for a traditional two or three support unit).
- bi-convex ($R_1 = R_2 = 150$ mm) four bridge resonator. The maximal sensitivity is lower than 10^{-9}/g.

In any case, no residual frequency deviation is observed when the acceleration is suppressed. Recent theoretical studies have shown the influence of support configuration[8] or slight dissymetries[9] on accelerometric sensitivity. Application of these results to B.V.A.$_2$ resonators appear as rather complex because of the great variety and special features of the support configurations. Experimental results confirm the great influence of the fixation and the interest of bi-convex contours.

4 - Other cuts and other frequencies :

B.V.A.$_2$ resonators have been made using other cuts especially S C cuts. (5 MHz fifth and third overtones 10 MHz third overtone). Interesting results have been obtained (especially much lower amplitude frequency effect).

The acceleration sensitivity is found to depend largely on some parameters and especially on the fixation configuration and evaluation (we preferentially use a four bridges support configuration).

Resonators 100 MHz fifth overtone have also been constructed and encouraging results have been obtained (high Q factors and easy frequency adjustement).

5 - Evolution and cost of the fabrication processes :

Over one hundred crystals have been evaluated, generally unit by unit. When greater quantities are made some operations can be simplified (especially frequency adjustement). To our experience, it appears that the fabrication cost of a B.V.A.$_2$ unit can be reduced to 1.2 or 1.5 time the cost of a traditional unit of the same frequency.

Conclusions

By use of a fixation made out of quartz the discontinuities and the stresses, usually caused by the traditional bonding processes, are avoided. The fixation location and characteristics are very precisely known. Since the electrodes are located very close to the active surface of the vibrating crystal, the frequency of the device can be easily adjusted. Nevertheless the gaps evaluation allows a very accurate frequency adjustement.

As consequences, very low acoustic losses and improved stabilities are obtained. It also appears that some properties related to acceleration effects are interesting (especially there is no permanent residual frequency deviation).

B.V.A.$_2$ resonators are interesting for fundamental studies, since their structure is very different from the usual. (precision of fixation means, properties related to heat transfer and crystal's noise contribution, additional construction parameters,...).

Those provisional results can provide direction for future research in the field of uncoated resonators and indicate promissive developpments.

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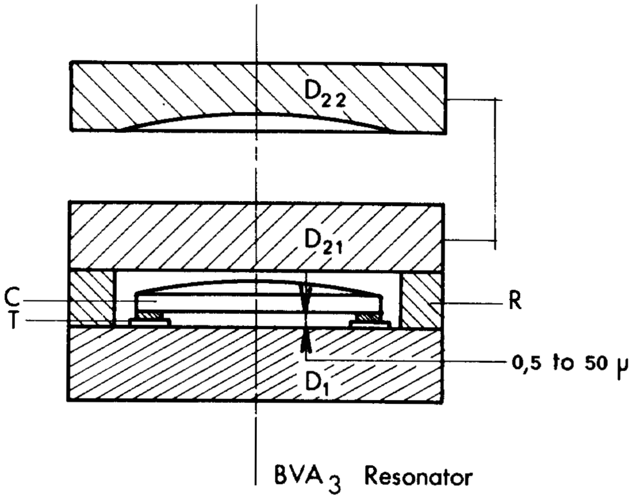

Figure 1. BVA$_3$ Resonator

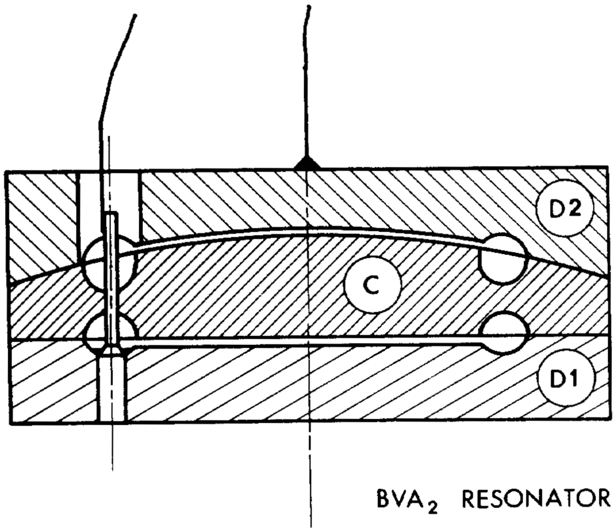

Figure 2. BVA$_2$ Resonator

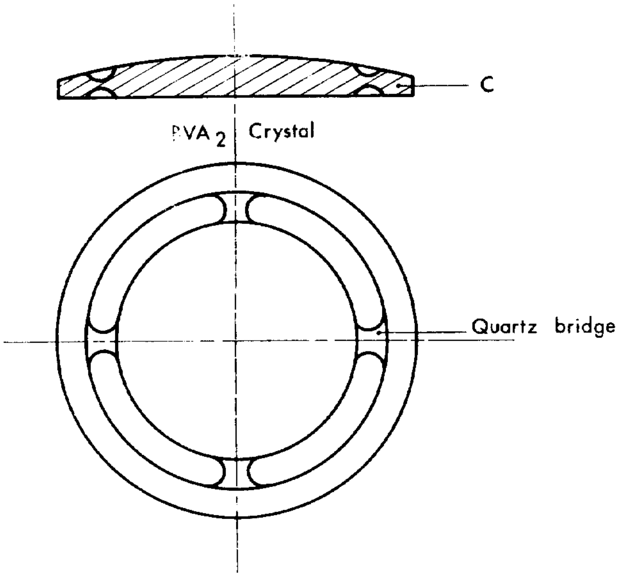

Figure 3. BVA_2 Crystal

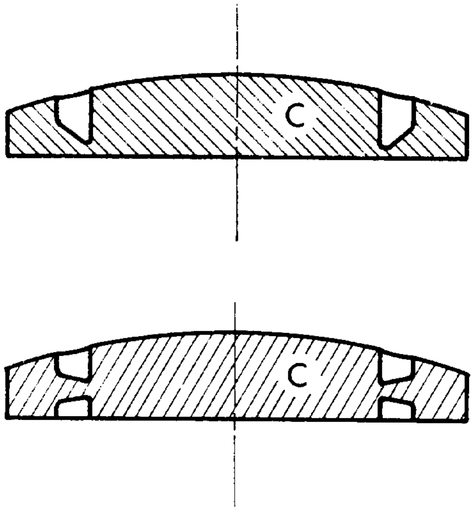

Figure 3a. BVA_2 Crystal - Single Bridge

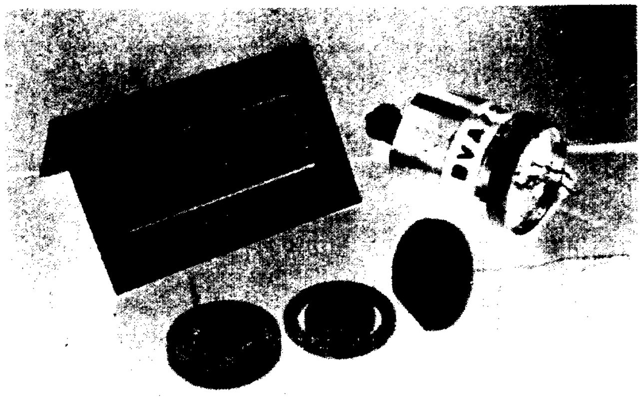

Figure 5. BVA_2 Resonator

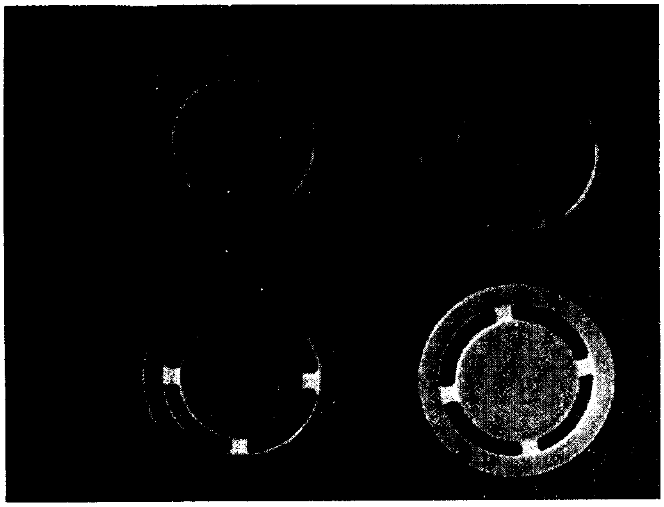

Figure 4. BVA_2 Crystal

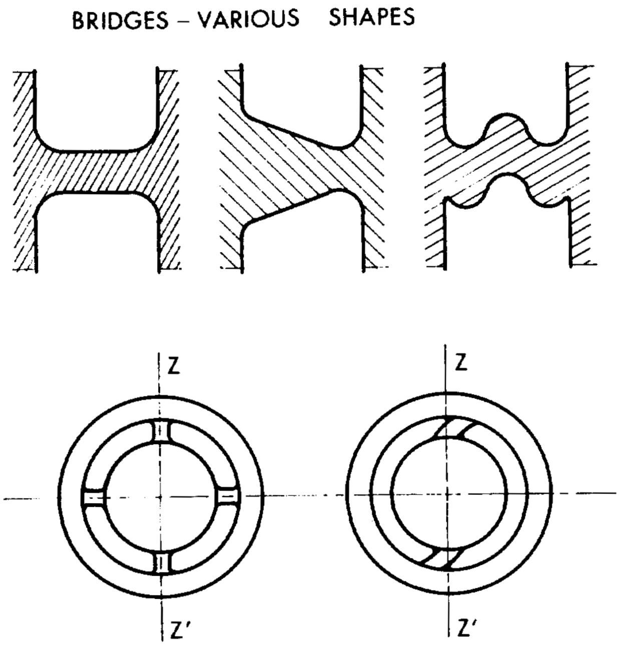

Figure 6. Bridges - Various Shapes

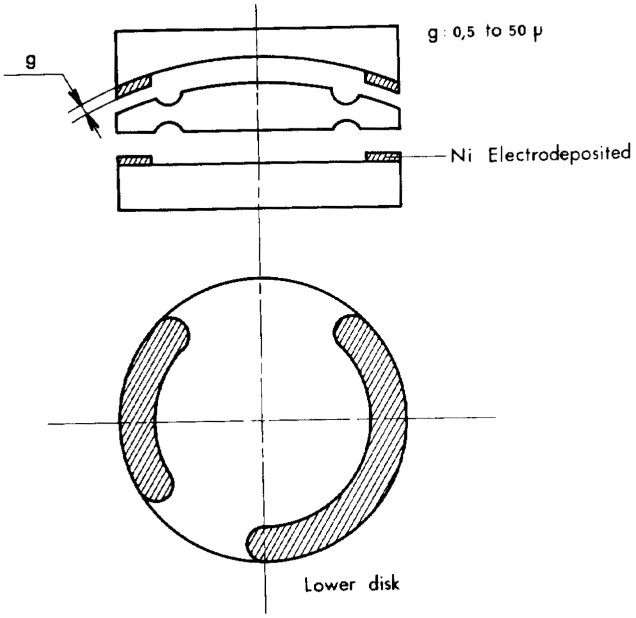

Figure 7. BVA_2 Resonator

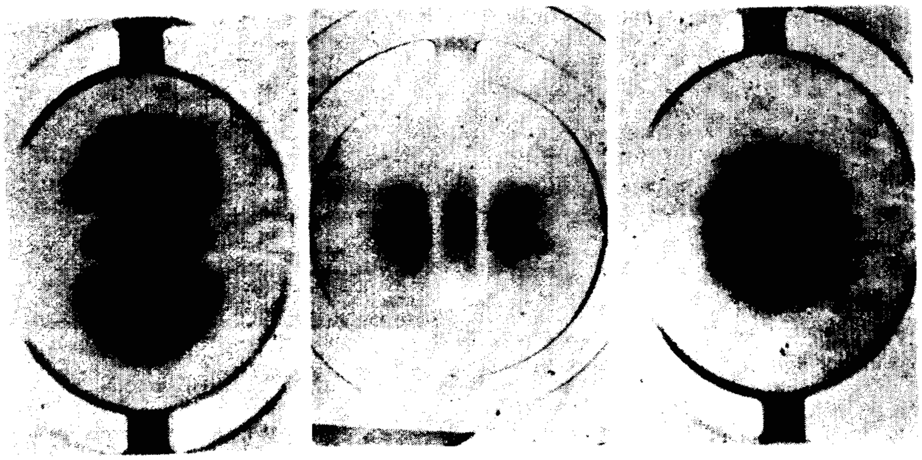

Figure 8. S.I.D. or Lang topographs