HISTORICAL REVIEW OF MEASUREMENTS USING INVAR WIRES IN SERBIA

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Key words: invar wire, history of measurement, trigonometric network

SUMMARY

Precise measurement of long lengths, especially in 1st order trigonometric networks, was always a problem to geodesists, Lengths should be measured in order to define the scale of a network. Thanks to E. Snelius and his work [5], a shorter length could be measured in a flat land, and than one could transfer its scale to a length between two trigonometric points, only by measuring angles. Nevertheless, it was not able to perform such measurements with the sufficient accuracy. The lengths were measured by wooden or metal levers, but the required accuracy needed for scale definition of the trigonometric networks was reached not until the invention of invar wires.

Serbia was one of the first countries obtaining and using the invar wires for the length measurements within the 1st order trigonometric network. The appearance of the invar wires and the Jäderin device for the length measurement coincided with the work on 1st order triangulation network in Serbia. In the beginning of 20th century, Serbian general Stevan Bošković was attending the training on triangulation procedures in France. In the same time, the invar wires were testing in the same place. Gen. Bošković realized the possibilities of using the invar wires in geodesy. Thanks to him, first measurements with the invar wires in Serbia were performed in 1904. One of the invar wires used in the measurements was numbered with "0" (zero).

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1. INTRODUCTION

W. Snellius has performed measurements considered as a basis of horizontal networks, introducing the triangulation with angles measured with several arc minutes accuracy. In 1615, he presented the basis of arc meridian measurements, by including a short, but directly measured baseline in his triangulation. The work of Snellius, and later on, Piccard and French expeditions, have showed that terrestrial measurements of the angles and, rarely, the lengths, are suitable for relative horizontal positioning of points. Calibrated wooden bars were used for the baseline length measurements during the meridian arc campaign [10]. The idea is reflected by Fig. 1. Instruments needed for the measurements have become more precise and simpler to use. Thanks to that, a development of the horizontal (trigonometric) networks with the point positions obtained by terrestrial measurements started in all parts of Europe, including the Serbian Kingdom.

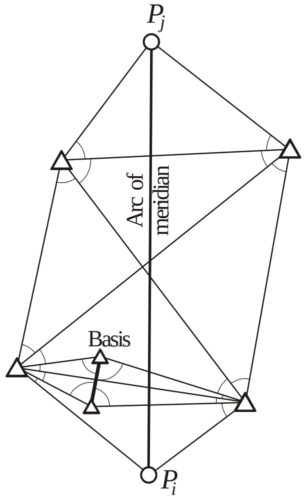


Fig. 1: Measuring the length of a meridian arc

The main problem with the development of the national 1st order triangulation networks was not the angle measurements, but rather how to measure a length (baseline) with the sufficient accuracy. Time span of this development covers the period from the beginning of XIX, up to mid XX century. In that period (before the invention of electro-optical distance meters) a different equipment was used for length measurements, from chains and bars to the invar wires.

2. THE LENGTH MEASUREMENTS

n the beginning, the length measurements were performed by measuring tapes, metal chains or wooden stuffs, which were always calibrated. The chain for the length measurements (Fig. 2) has consisted of several pieces 1 m long, joined with special pieces 2, 5, and 10 m long, which were used as metres markers. Big links were connected to the ends of the chains. Wedges were squeezed through the links, in order to stretch the chain. The accuracy of such lengths was sufficient only for land surveying purposes.

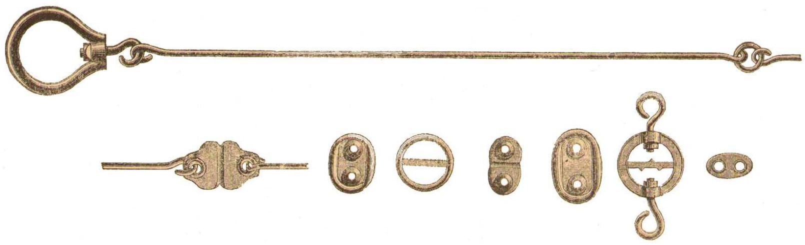


Fig. 2: A chain for length measurements

Special wooden (Fig. 3) or metal, calibrated stuffs were used for the precise length measurements. The wooden stuffs were made of the high quality dry wood, then cooked in oil and, accordingly, protected from moisture penetration. The stuffs were 4 m long, with several centimetres long metal fittings at the ends. A half cylindrical piece was soldered to the end with the fittings, which represented the start of the stuff division. The other end contained the mechanism in the form of a knee (marked with *d* in Fig. 3), which could be precisely moved. It was used for reading the parts of millimetres. Placing and levelling the stuff was done by using iron stakes (*E* and *F*, Fig. 3), which passed through the cylinders (*C* and *D*, Fig. 3) on the stuff. Some stuffs, mainly made of metal, contained microscopic micrometres for reaching a better accuracy. Temperature was always measured when the precise stuffs were used, for entering the corrections for the length changes, caused by the temperature coefficient of a material [7]. With this equipment, one could measure approximately 300 m per day. With latter improvements, that increases up to 800 m per day.

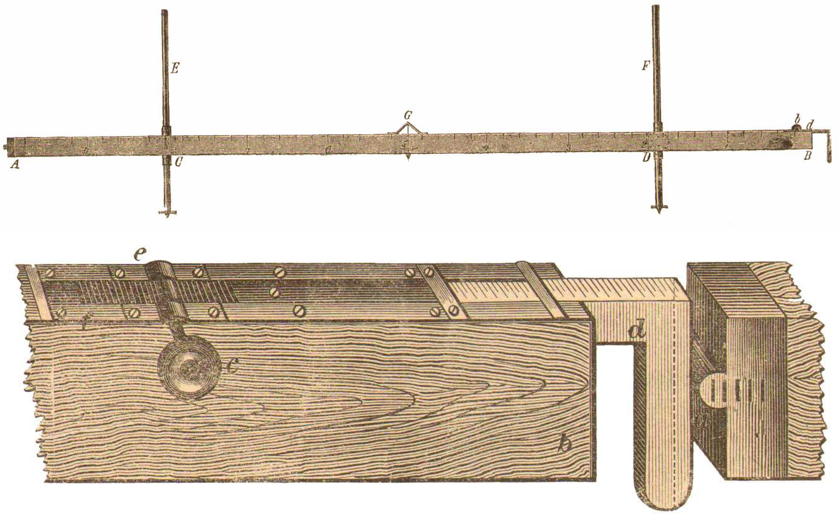


Fig. 3: Precise wooden stuff

A huge advantage in the precise length measurement was represented by the appearance of the Jäderin basis apparatus in 1880 (Fig. 4). Practically, it is an advanced length measuring by the chain. The only significant differences are the usage of one wire, instead of three separated ones, and a specially constructed mechanism for stretching the wires. The wires were made of iron, 24 m long, and stretched by 1 kg balances on both ends of the wire. Also, this apparatus was read in a special way - at the ends of the wires there were rulers for accurate reading of the length. The tripods used for hanging the wires were, approximately, 60 cm high.

The main drawback of the Jäderin basis apparatus was the same as with the previous models - the large temperature coefficient of the material, which made the precise temperature measurement necessary.

This problem was overcome in 1896 when René Benoît and Charles Édouard Guillaume from the International Bureau of Weights and Measures invented invar, the alloy consisted of 36% of nickel, 63,3% of steel, with traces of manganese (0,4%) and carbon (0,1%). Due to its content, invar is often called FeNi36. This alloy has the uniquely low coefficient of the thermal expansion of about 1.2×10^{-6} K^{-1} (1.2 ppm/°C).

Fig. 4: Jäderin apparatus

Production of devices for the precise length measurement based on the Jäderin basis apparatus started after the invention of invar. There were certain changes in the design of the wires and the accessories. The diameter of the wires remained the same - 1,65 mm. Special rulers, with the triangular cross-section, used for reading the parts of millimetres, were put at the ends of the wires. The rulers (Fig. 5) were placed next to special designed benchmarks (Fig. 6), which were mounted to supports and served for accurate vertical alignment (with the tripod) over the points between which the length was measured. The tripods with straining pulleys (Fig. 7) were used for stretching the wires. A rope was squeezed over the straining pulleys with one end tied to the invar wire, and second with a 10 kg balance attached to it. Jules Carpentier from Paris developed and produced the complete apparatus for the invar wires measurement.

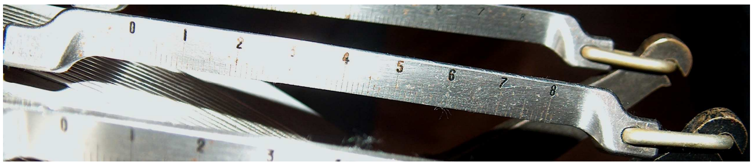


Fig. 5: The ruler

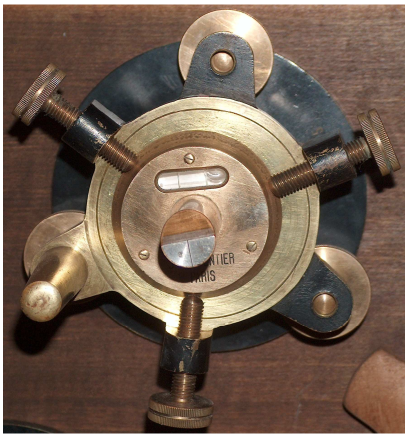


Fig. 6: The support with the benchmark

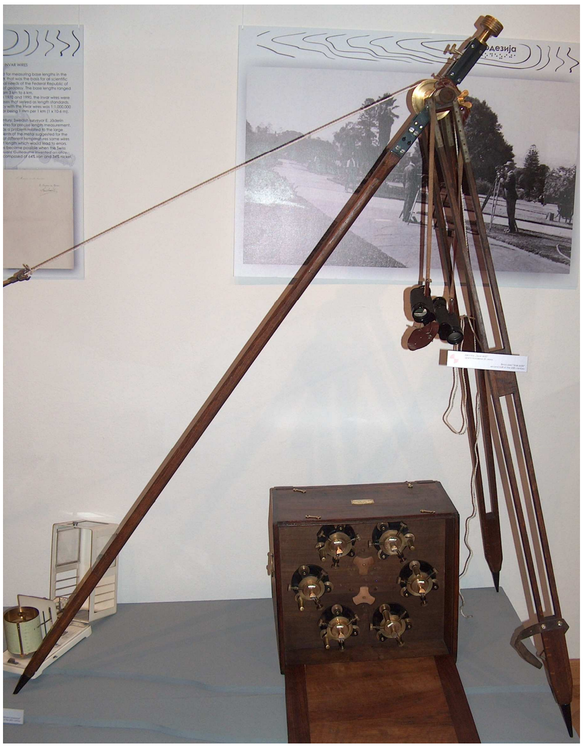


Fig. 7: The tripod for stretching the wires, with the set of supports in the box

3. LENGTH MEASUREMENTS IN SERBIA

3.1. Serbian 1st order trigonometric network (TNS)

Austrian Military Geographic Institute (Militar Geogräphischen Institut - MGI) began the works on development of the 1st order trigonometric network (TN1) in Balkans region in 1872 [8]. The area covered the territory of today's Serbia and Montenegro. The development of the network was based on a chain of triangles, divided into specific parts [2], [3]. Each part defined its own network datum by the coordinates of MGI chain points, or previously adjusted parts, using the parameters of Bessel 1841 ellipsoid.

In the area of the Serbian Kingdom, the works on trigonometric network over the part of its territory began in 1887, conducted by Prof-ing. Milan J. Andonović. The works were performed by the newly founded Geodetic Institute within the High School (today, University of Belgrade). The baseline near the city of Paraćin was selected for test measurements with the basis apparatus [1]. The works were stopped in 1894, and continued in 1899 by the Geographic Section of the General Staff of the Serbian Army (today, Military Geographic Institute - VGI). Along with measuring the horizontal angles and the baselines, astro-geodetic determinations were performed, too. Latitudes and azimuths were determined at thirty triangulation points. Since 1919, a new organization, General Cadastre Board (later changed the name into the Department of Cadastre and State Goods) has taken a significant part in the state survey, both in the areas of field and computational works. The network was expanded to Macedonia [6]. The adjustment of the measurements started in the autumn 1925 and concluded in the March 1927. Due to technical and computational capabilities, the conditional method with iterations was chosen for the adjustment of the network. The point coordinates came into use in 1928 and, up to day, they are still the official coordinates for state survey and cadastre in Serbia.

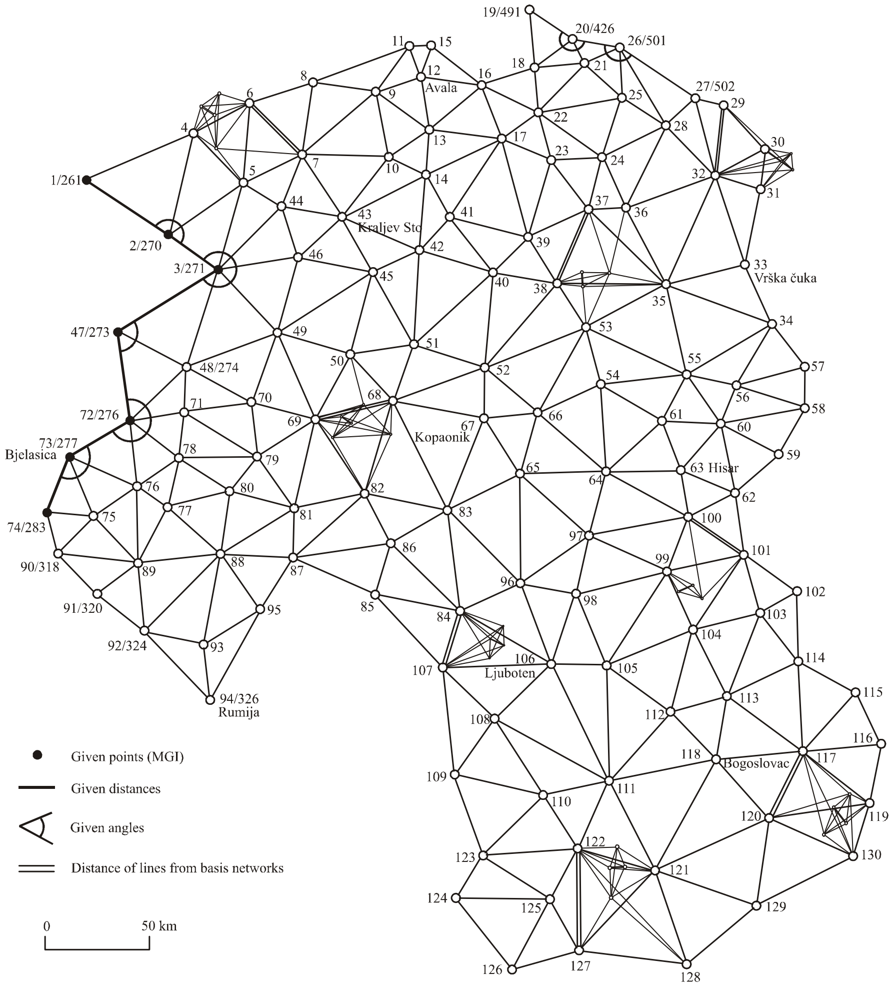


Fig. 8: TMS - 1900-1927 epoch

A significant role in the development of TNS, conceptually and in the length measurements, has had general Stevan Bošković (later, the Head of VGI). A few years after the cancellation of the first work on TNS, Serbian officials sent gen. Bošković to a study visit to Russia, in order to learn everything considering the 1st order triangulation networks. Before that, all survey was conducted graphically, without a mathematically defined background. After his visit to Russia, Bošković travelled to France, just in the same time when the test measurements with the new technique - invar wires, were performed. Since he was there in person, he realized the possibilities of the new technology for the precise length measurements. Thanks to his efforts and connections, a Carpentier set for the precise length measurements with invar wires came to Serbia (tripods, supports, auxiliary equipment and six invar wires). One of these wires was numbered as “0” (zero), and two others were A_{26} and A_{39}.

During the determination of the scale of TNS, the lengths measured by the invar wires were used, obtained by the indirect measurements of the baselines in the basis networks (Fig. 8). The baselines were fixed by stone pillars (the ends of the baselines and some sections between which the lengths were measured) with carved crosses. Totally eight baselines were measured in TNS - four in Serbia in 1904, and four in Macedonia during 1922 and 1924. All baseline measurements are characterized by the measurements performed with just one wire, which is called “operational”, while the others were used for testing the length of the operational one. In the first epoch, the length of the wire is tested by two wires, while in the next epoch all available wires were used (Tab. 1). Such procedure was applied in order to assure faster measurements of the length (for example, the 5,6 km long length of the baseline Paraćin is measured in four days, i.e. the baseline was separated into four sections). All wires were sent to Paris for calibration [4]. The certificates of the wires calibration are saved and still exist (Fig. 9). During the calibration, besides the accurate length of the wire, the temperature change of the wire length was determined (Fig. 10).

Tab. 1: Baselines and basis networks

Name of network	D base-line. [km]	D exit b.line [km]	Year of mesure-ment	# of wires	# of mea.	Relative baseline error 1:	# of pts.	# of dirs.	# of Δ	$f_{\Delta \max}$ ["]	$(m_\omega)_\Delta$ ± ["]	$(m_\omega)_{izr}$ ± ["]
Paraćin	5,60	36,61	1904.	1(1)	2	938 000	8	40	22	1,84	0,60	0,98
Negotin	4,66	33,99	1904.	1(1)	2	910 000	7	38	23	2,87	0,78	1,46
Vranje	4,97	32,03	1904.	1(1)	2	1 076 000	6	22	8	0,85	0,22	0,21
Loznica	5,03	35,21	1904.	1(1)	2	1 034 000	8	42	26	2,81	0,65	0,85
Prizren	5,38	27,67	1922.	1(5)	2	1 037 000	6	30	16	2,99	0,95	0,94
Strumica	6,62	34,27	1922.	1(5)	2	1 106 000	8	42	24	2,40	0,70	0,76
Prilep	5,98	48,14	1922.	1(5)	2	1 316 000	8	44	28	2,32	0,62	1,04
Sjenica	5,57	36,62	1924.	1(5)	2	798 000	9	48	27	4,14	0,98	1,20

The total mean error of the baseline equals to the sum of all individual error sources. The relative error is the ratio of total mean error and the length of the baseline.

The lengths of the specific stakes, which were measured by the invar wires, were corrected for the deviations of the wire length from the nominal value, for the temperature change influence and for the non-symmetry of a catenary. Then the lengths are reduced to the horizon. Total length of the baseline is obtained as a sum of the all stakes measured by the wires and the measured remaining parts, because of the fact that the baselines length is not dividable by 24 (which is the length of the wire). That is why the remaining part is measured by a 12 m long invar measuring tape.

1907

BUREAU INTERNATIONAL DES POIDS ET MESURES

1904-1907

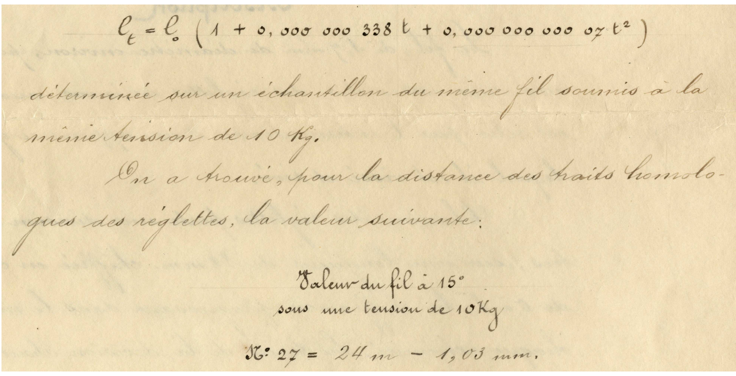
CERTIFICAT

d'un Fil en invar N 27

appartenant

au Service Géographique de l'Armée Serbe

Fig. 9: Front page of the certificate



$$l_t = l_0 \left(1 + 0,000\,000\,338\, t + 0,000\,000\,000\,07 \cdot t^2\right)$$

déterminée sur un échantillon du même fil soumis à la même tension de 10 Kg.

On a trouvé, pour la distance des traits homologues des réglettes, la valeur suivante:

Valeur du fil à 15°
sous une tension de 10 Kg

N° 27 = 24 m − 1,03 mm.

Fig. 10: Certificate excerpt: temperature change and the wire length

3.2. Measurements performed by the Institute of Geodesy

Just after the completion of the network in Serbia, and especially after the completion of the ex Yugoslavian network in 1949, it was realized that there is a mismatching within the network [9]. It was related to, so called, closure conditions - the calculation of the stake lengths based on the measured angles in the triangle chains using the sine equation of the triangle, starting from one known length. That principle was used many times when calculating the length of the exit baselines in the basis networks (for example, Paraćin-Prizren). Obtained results were ambiguous due to the available calculation devices, but mostly due to the poor reliability of the networks. So, it was decided to process and adjust all the basis networks again, without repeating the measurements. However, it did not bring any new results, because the lengths of the exit baselines were just slightly changed.

In most cases, the mismatching was noticed in basis network Paraćin. After the unsuccessful recalculation, it was decided to repeat the measurements. It was done in 1981. by the Institute of Geodesy of the Faculty of Civil Engineering in Belgrade. Prior to that, the Republic Governmental Authority reconstructed the Paraćin baseline: on the end points the pyramids with protective covers were raised, using the method of three tripods (Fig. 11). Unlike 1904, when there were only three pillars between the end points, now there are 21 pillars on different distances from the starting baseline point (8 at 24 m, 3 at 192 m, 9 at 480 m and 1 at 504 m). Since the baseline is not dividable by 24, each stake is expanded for 1,5 cm, which makes the last one 8 m long and, therefore, measurable with the 8 m long invar tape, which was a part of the measuring set.

Each stake is measured with the all four wires from the set, with six readings of one wire, forward and backward. Due to that, and the fact that the whole crew performed such measures for the first time, the measurements lasted for 12 days. The procedure consisted of assembling the tripods, aligning them, levelling and disassembling the tripods. In the first days of the measuring campaign, the measurements lasted for 15-16 hours/day, and later on, much shorter (10-11 hours/day). During each measurement with the wires, the air temperature is measured, too.

The length of the each stake, for each wire, is corrected for:

- deviation of the wire length from the nominal value (from the certificate),
- change of the wire length due to the temperature difference (from the certificate),
- non-symmetry of the catenary,
- inclination of the reading scales, and
- reduction to the horizon.

After the completion of the measurements, the stake lengths between all the pillars are calculated, as well as, the length of the whole baseline. Finally, the baseline length is corrected for the difference of the gravity field acceleration during the measurements and the calibration. The accuracy of the baseline, calculated from the deviations of certain measurements from the arithmetic mean, was 1:1 000 000 or 5,75 mm (the baseline is 5603 m long). Thanks to such the high accuracy, the baseline served for a long time as a calibration base for all kinds of distance meters.

Fig. 11: Reconstructed end point of the Paraćin basis and one of the pillars

Comparing its value with the length determined in 1904, it was noticed that there is an error of 1 dm in the first measurement of the baseline, which caused the error of the exit baseline of 1 m (determined by the recalculation of the basis network). It is confirmed later, by a direct measurement between the 1st order trigonometric points. With the new value of the exit baseline, all the closure conditions satisfied the requested preconditions. There were no conclusions considering the reason of that error. The section pillars from the 1904 were saved and the measurements with the precise electro-optical distance meters between them were performed. According to these, and the measuring data by sections from 1904, no systematic influence was found, because the differences matching the accuracy limits.

4. CONCLUSION

For many years, the accurate measurement of the long lengths made a huge problem to the surveyors. The distances were measured with the different equipment, like the chains or the straining levers. The appearance of the Jäderin basis apparatus and the invar wires made the accurate measurement of the lengths possible. Thanks to that, based on the work of Snelius [5], the lengths needed for defining the scale of the trigonometric networks could be measured indirectly - from the basis networks.

Among the first countries that used that way, by measurements using the invar wires, was Serbia, thanks to academic general Stevan Bošković. He resided in France during the initial measurements with the invar wires, joined the measurement procedures, and considered the possibilities of that brand new method. That is why he asked, and succeeded in his efforts to get one set of the invar wires for Serbia. First measurements in Serbia were performed in 1904, characterized by measurements performed by only one wire (operational), while the others served for the verification of the operational one.

Institute of Geodesy of the Faculty of Civil Engineering measured in 1981 the Paraćin baseline again, finding the error in the first (1904) measurements, which produced the error of the exit side of 1 m. Based on the following measurements, no conclusion about the reasons of the error is drawn. The wrong value of the baseline is used in the adjustment of 1st order triangulation network in Serbia. The only acceptable explanation is the error is made during the measurement of the remaining parts of the stakes by the invar tapes. The obtained coordinates, with that gross error, are still official and in use.

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BIOGRAPHICAL NOTES

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