Future challenge in the calibration of high-resolution hydrographic multi-sensor systems

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Key words: Ship calibration, hydrographic multi-sensor system, underwater laser scanner, system integration

SUMMARY

Multibeam echosounders offer a high coverage in bathymetric data acquisition. At present, however, the resolution and achievable accuracy are limited. Under optimal conditions, these are in the range of several centimeters for short distances. New developments in (optical) underwater measurement technology, like underwater laser scanners, promise higher resolutions, flexibly adjustable scan patterns and high measurement accuracy. The next step is to use these instruments for kinematic data acquisition, for which the instruments are installed on mobile platforms like surveying vessels. They become a component in a hydrographic multi-sensor system. In order to achieve a high (geometric) data quality of the measured point cloud, an accurate and reliable calibration of the complete multi-sensor system is required. Additionally, high-precision synchronization of the measurement data is required for kinematic measurements with the underwater laser scanner.
In a first step, a solution for a sensor alignment survey on board of small surveying vessels, like the HCU surveying vessel DVocean, is developed. This includes the definition of a suitable ship coordinate system and its realization, the selection of adequate surveying instruments (e.g. total station, laser tracker) as well as adapted measurement concepts to acquire hidden points.

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1. INTRODUCTION

The acquisition of point clouds is common in hydrography for a long time, since the first multibeam echosounder (MBES) was used. With the introduction of this measurement system, the requirements concerning the compensation of vessel motion increased. Thereby, this also increased the demands on the vessel alignment survey. The offsets between the Inertial Measurement Unit (IMU), GNSS antennas and the MBES transceiver have to be determined precisely as a 4D vector (lever arm and latency). Additionally, the installation angles or the misalignment angles between the individual instruments have to be known precisely.

Nowadays, modern MBES have a very small beam width, especially when high frequencies are used. For example, the Kongsberg EM2040P MKII is offering a beam width of 0.6° for a frequency of 700 kHz (Kongsberg 2022). In order to benefit from this resolution, Brüggemann (2013) emphasizes that the lever arms between the instrument reference points can be determined easily with an uncertainty of better than 5 mm. The uncertainties of the installation angles of the inertial measurement unit should reach at least the same level like the measurement accuracy of the instrument itself. An uncertainty that is even lower than the angular resolution would be preferable here. If the installation angles have to be derived from measured point coordinates, the required coordinate uncertainty might be raised up to better than 0.5 mm (Brüggemann 2013), which significantly increases the requirements for the geometric quality of the calibration. This poses a particular challenge when calibrating small survey vessels with limited free space and many visual obstacles. Measurement uncertainties in this range can be achieved by a laser tracker in particular. However, high-precision total stations can also provide point coordinates with sufficient precision if measurements are carried out in multiple sets and are adjusted in a geodetic network.

In recent years, also optical systems have been developed for underwater applications. As a part of this emerging market, more and more hydrographic LiDAR instruments are available. Next to the UAV-based bathymetric laser scanners, which are particularly suitable for shallower water areas, also underwater laser scanners are available. Within the last few years underwater laser scanners with a rotating laser beam have also been developed.

Figure 1: Underwater laser scanner ULi from Fraunhofer IPM

One of these instruments, the underwater LiDAR system (ULi) from Fraunhofer Institute for Physical Measurement Techniques (IPM), is currently installed on a pole on the HCU owned surveying vessel DVocean (Figure 1). This instrument consists of a laser with a wavelength of 532 nm and uses the time-of flight principle for the distance measurements (Fraunhofer IPM, 2024). It has a sampling frequency of up to 100,000 points per second and offers a precision of better than 1 cm in clear water. Its measurement range is approximately two secchi depth and is therefore depending to the turbidity of the water. The scan pattern of ULi can be adapted within a 44° field-of-view (Fraunhofer IPM, 2024). In order to be able to record kinematically high-resolution point clouds of underwater structures, highly precise boresight angles and lever arms must also be determined for this instrument. For this task, the use of a laser tracker is recommended which has to be stationed in a predefined ship coordinate system.

The resulting point clouds can be used as a base for change detection and monitoring tasks. So, the calibrated underwater laser scanner will contribute to the creation of a data base for a sustainable maintenance and use of built underwater structures, e.g. bridge foundations or quay walls, but also help to preserve natural structures for future generations.

2. METHODS: SHIP CALIBRATION

There are different approaches and methods to perform a calibration of the hydrographic measurement system on board a surveying vessel (ship calibration). Generally, seven parameters have to be determined,

- Latency: time delay between GNSS time and the echo sounder or laser scanner time stamp,
- Lever arm: 3 translation parameters representing the geometrical offsets between GNSS antenna and other installed (hydrographic) instruments,
- Boresight angles: 3 rotation angles representing the misalignment angles (roll-, pitch- and yaw-component) between the internal coordinate systems of the IMU and other installed instruments.

Some of the calibration methods are summarized here, even if the focus is then on determining the lever arms.

2.1 Ship coordinate system

An essential precondition for a ship calibration is a clearly defined ship coordinate system. There are multiple variants to establish it. Theoretically it would be perfect to select the center of origin to be identic with the center of the mass of the ship (center of gravity). Especially on small, transportable surveying vessels the physical center of mass (center of gravity) depends to possibly varying loads (Lekkerkerk, 2012). Simulations for the HCU surveying vessel DVocean indicate that varying loading conditions caused by the presence or absence of the scientific staff already might shift the center of mass more the 5 cm along the longitudinal axis of the vessel (Yermakovych, 2022). Yermakovych (2022) calculates that it can even be shifted more than 20 cm if the scientific staff works with probes or a towfish in the stern area of the ship.
Another option is to select a clearly defined point on the ship or a hydrographic component to be the center of origin. Often this point is related to one of the installed instruments (e.g. marked reference point on the IMU housing or internal IMU reference point). However, on small vessels, especially in the scientific field, changes in the sensor configuration might be required and the instrument with the marked center of origin might be replaced. To overcome this problem, the point of origin of the vessel coordinate system can be defined by a virtual point. Brüggemann (2013) suggests to locate the point of origin in the center of the stern side in the waterline plane. The benefit of this approach is that the corresponding reference frame can be realized before the installation of the instruments. For the its realization, multiple fixed points with a clearly defined marking have to be mounted on the ship (*reference frame*). They should be distributed all around the ship to offer a good visibility of at least three fixed points from all sides. Knowing their coordinates in the ship coordinate system, they can be used to determine the lever arms for newly installed instruments.

The alignment of the coordinate axes has to be specified with respect to the known geometry of the ship. Generally, one axis is aligned in longitudinal direction. Brüggemann (2013) and Kongsberg (2020) identify this axis as x-axis. The z-axis is perpendicular to a clearly defined height reference plane and usually pointing upwards. Lekkerkerk (2012) and Brüggemann (2013) suggest to use the waterline plane for this purpose. The y-axis is completing the orthogonal coordinate system. For the HCU surveying vessel DVocean, a right-handed coordinate system is used which is following the definition of Brüggemann (2013).

2.2 Component-wise calibration

The objective of a component calibration is to determine the position and – sometimes – the installation angles of all relevant hydrographic measurement components with respect to the previously defined vessel coordinate system. Even if measuring tape is sometimes used to determine the required lever arms, it is recommended to use a more accurate surveying method for the ship calibration. The use of a highly precise total station or a laser tracker offers a sufficient measurement accuracy to determine the coordinates of the instrument reference points with the aimed accuracy. This potential can be best utilized when the ship is jacked up on land.

There are multiple set-up points for the surveying instrument around the ship. This station configuration should allow that each defined point on a hydrographic instrument can be targeted from at least two stations of the surveying instrument from different directions (Brüggemann, 2013). This configuration increases the reliability of the survey because it helps to detect measurement outliers. The precision of the survey should be raised by repeating the measurements in multiple sets to highly precise prisms. Precision prisms or special reflectors for monitoring tasks are available with an aiming accuracy of better than 1 mm (e.g. 0.2 mm for spherical mounted reflectors). Even if the desired coordinate accuracy can be achieved with this measuring equipment without problems, this high-precision equipment is required to determine the installation angles of sensors like the MBES transceiver. Usually, the installation angles are determined with a in situ-calibration (chapt. 2.3). However, there are also cases in which the measurement area of a ship does not allow a field calibration to be carried out, e.g. in man-made channels. The determination of installation angles from individual measurement points is challenging because the dimensions of the transceivers are often small on inland surveying vessels. If only points are measured directly on the transducer surface, each point has to be measured with an accuracy of less than 0.5 mm to derive suitable installation angles Brüggemann (2013). The solution of Brüggemann (2013) and Brüggemann (2018) includes the mounting of a longer base plate on the transducer surface which is attached in varying orientations. By surveying at least four points on this extended plane, the geometric accuracy requirements for the individual point coordinates can be reduced slightly. Still, latency is not determined.

2.3 In-situ calibration

2.3.1 Patch Test

The Patch Test is a well established method to determine the latency between GNSS time and usually the MBES and the boresight angles between the internal coordinate system of the IMU and the MBES (e.g. Brennan 2017, Guériot 2020). It requires an adequate underwater measurement area with flat parts (determination of the roll-component), areas with a significant slope (determination of the pitch-component and latency) and preferably distinct features (determination of the yaw-component). However, the lever arms between the sensors must still be determined by a component-wise calibration.

Depending on the acquisition software used and the implemented rotational sequence, a specific sequence is required to determine the angles. As the alignment of the point clouds and therefore the boresight angles themselves are depending to the measurement area, the quality of the point cloud and as well as manual or automatic adjustments, the results can vary from scenario to scenario. Although the MBES installation is still represented in a suitable geometric quality, it becomes difficult to monitor the stability of the boresight angles over a longer period of time.

2.3.2 Multibeam System Parameters Automatic Calibration (MSPAC)

In contrast to the patch test the MSPAC intends to determine additionally the lever arm between MBES internal reference point and the phase center of a defined GNSS antenna antenna and bases its computation on combined statistical analysis. It contains different modules,

- MBES INS Latency Automatic Calibration (MILAC) ((ENSTA 2017),
- MBES INS Boresight Automatic Calibration (MIBAC) (ENSTA 2017, CIDCO 2022) and
- Lever Arm Automatic Calibration (LAAC).

Within only four lines over a sloped area all three position angle corrections are determined together with an automatic data selection algorithm and statistical adjustment based on the least square method in small, differently sized patches of data. So far, this calibration routine is however only available in individual commercial software.

3. CALIBRATION PROCEDURE: STATE-OF-THE-ART AND FUTURE

Here, the hydrographic measurement system of the surveying vessel DVocean is calibrated. The DVocean is designed for surveys in shallow waters like inland waterways. It has a length of 8.00 m and a width of 2.55 m, including a cabin. All lever arms on the DVocean are determined with respect to a previously defined coordinate system. Its definition is aligned to the suggestions of Brüggemann (2013): The x-axis is pointing from the center of stern in forward direction, the z-axis is pointing upward and the y-axis completes the right-handed coordinate system. Initially, the coordinates of all instrument reference points, which are published by the corresponding manufacturers, are determined with respect to the ship coordinate system. Considering them as 3D vectors, the required lever arms can be calculated by vector addition.

Here, the total station Leica TS60 is used for the measurements, which can reach a standard deviation of 0,5" for angular measurements and of 0.6 mm + 1 ppm for distance measurements (with reflector) (Leica, 2020). The minumum measurement distance of this instrument is 1.5 m. Alternatively, a laser tracker can be used for this task. To acquire all required marked points on the hydrographic instruments preferably from two total station positions, five tripods are set up around the ship. They are part of the geodetic network. Due to the spatial limitations around the ship, the maximum measured distances is only approx. 15 m. This set-up configuration also allows the verification of the stability of the defined fixed points on the vessel. They are distributed all over the vessel to make sure that multiple points are visible from each position of the total station. They are signalized with centering plates to insert magnetic adapters and spherical mounted reflectors (SMRs) (Figure 2) like it is depicted by Brüggemann et al. (2018). These reflectors are compatible with both the total station and the laser tracker and are flexible in their spatial alignement. After completing the survey, the magnetic adapters and the SMRs can be removed and inserted again with a high repeatability for the next survey. Other instruments, e.g. GNSS antennas are fixed on the ship by screw fittings. In these cases, (mini) round prisms are directely fixed on the screw fittings (under consideration of vertical offsets).

The measurements are executed in four sets (both faces) to be able to detect outliers and to increase accuracy.

Figure 2: Two fixed points on board the surveying vessel, signalized by SMRs

3.1 IMU

Especially on small surveying vessels, there is hardly enough space to set up a total station or a laser tracker inside the cabin. Therefore, the line of sight to the IMU or respectively the points with given coordinates in the instrument coordinate system are oven covered. To overcome this problem, theoretically two approaches can be applied.

A reflector can be mounted on a thin extension stick with tip. If the tip is placed on the known point and the reflector is rotated around this point, all measured points lie on a sphere segment (Figure 3). Based on these measurements, the coordinates of the sphere center can be computed by solving the non-linear functional model

$$f(r, x_C, y_C, z_C) = \sqrt{(x_i - x_C)^2 + (y_i - y_C)^2 + (z_i - z_C)^2} - r, \tag{1}$$

where r – sphere radius = stick length + SMR radius,
x_C, y_C, z_C – coordinates of the sphere center,
x_i, y_i, z_i – coordinates of the measured SMR positions on the virtual sphere.

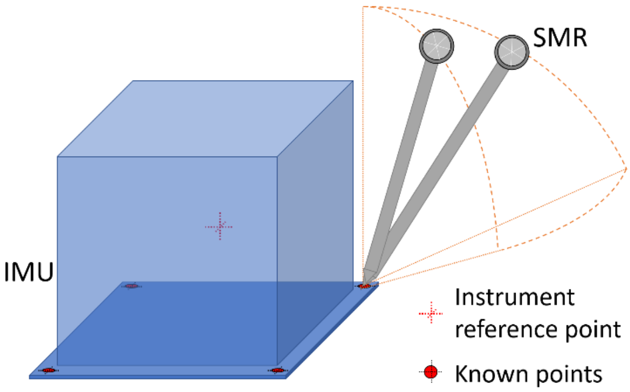

Figure 3: Representation of a known point (of the instrument coordinate system) by the sphere center

Next to the measurement accuracy of the used instrument, the accuracy of the station coordinates and the location of the measured point relative to the total station, the geometric quality of the estimated sphere center depends additionally on the number and the distribution of the measured points on the covered sphere segment as well as on the used reflector type. The resulting geometric accuracy of the sphere center is determined with a Monte Carlo simulation for a sphere radius of 20 cm. It is assumed that the station coordinates are known with an accuracy $\sigma_x = \sigma_y = \sigma_z = 0.5$ mm and that the measurement accuracy coincides with the given values for the Leica TS60. As expected, Monte-Carlo simulations demonstrate that the standard deviation of the estimated center coordinates is worse if the measured points are located within a narrow sphere segment (horizontal / vertical angle segment: 15° / 21°) compared to a sphere segment with an horizontal / vertical angle segment of 50° / 35° (middle-sized sphere segment) (Table 1). However, if the reflector only moves on the narrow sphere segment simulated here, an accuracy requirement of 5 mm cannot be met even with 20 measuring points. To perform an economically efficient survey, the number of measurements should be minimized, even if a higher amount of points will increase the accuracy of the center coordinates. The simulations also show that the centering accuracy of the used prism type will influence the geometric accuracy of the center coordinates if the number of measured points is relatively low. In this scenario two reflector types are considered, a SMR with a centering accuracy of 0.2 mm and a mini prism with a centering accuracy of 1 mm. The results in Table 1 indicate that 6 measured points with a wider distribution on the sphere should be sufficient to achieve the required accuracy of the center coordinates if a mini prism is used. By using a high precise SMR, even 4 sphere surface points result in a standard deviation better than 5 mm.

Table 1: Approximated 3D Standard deviation of the estimated sphere center by using different spatial distributions of (simualted) measurement points

	Narrow sphere segment			**Middle-sized sphere segment**		
	20 points	**10 points**	**6 points**	**10 points**	**6 points**	**4 points**
SMR	21.8 mm	23.1 mm	30.3 mm	2.5 mm	2.9 mm	3.8 mm
Mini prism	36.9 mm	38.7 mm	49.2 mm	4.0 mm	4.5 mm	6.0 mm

To increase the accuracy and speed up the measurements, a calibration frame can be fixed on top of the instruments housing (Figure 4). This prevents that the IMU housing itself interrupts the line of sight connection between the surveying instrument and the reflector on the known points. There are four SMR positions on this frame whose spatial offsets to the manufacturer's known points is calibrated in a laboratory environment with a laser tracker beforehand. On the ship, the calibration frame is set on the IMU and only the SMR positions have to be measured. In a 3D coordinate transformation, the given coordinates of the IMU reference point can be transformed into the used coordinate system or directly into the ship coordinate system. The frame is removed after the calibration.

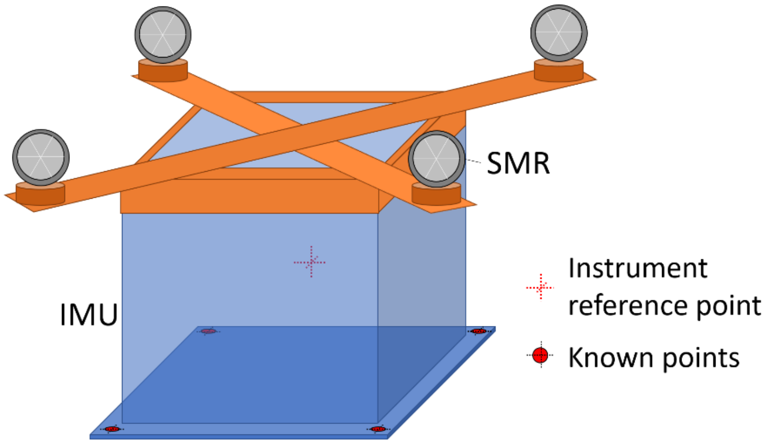

Figure 4: Simplified calibration frame for an IMU (e.g. iXBlue Hydrins)

3.2 Underwater laser scanner (ULi)

Like for the calibration of an IMU, the manufacturer can define fixed points on the housing of the underwater laser scanner. By signalizing these points with SMRs and knowing the position of the instrument reference point, its coordinates can be calculated in the super-ordinated coordinate system.
An alternative approach to determine the reference point coordinates involves scanning the cylindrical housing of the ULi. Since the position of the reference point and the orientation of the laser's zero direction (no deflection) is known with respect to the geometric model of the housing, fitting a reference geometry consisting of cylinders into the point cloud makes it possible to calculate its coordinates with respect to its center line. However, the slightly reflecting metal housing of the underwater laser scanner is difficult to be scanned with usual (terrestrial) laser scanners. In order to ensure a high accuracy, the manufacturer Fraunhofer IPM suggests to use a laser tracker or robot arm supported laser scanner. The geometric quality of the resulting point cloud and concurrently of the ULi reference point will be increased, if this laser scanner enables the detection of reflective surfaces with a high signal to noise ratio.

As the latency also has a major influence on the measurement result due to the high acquisition rate of the scanner, the time stamp must also be highly accurate. Using the commonly used Pulse-Per-Second (PPS) signal is not sufficient to synchronize up to 100.000 measurements per second. To overcome this issue a PTP (Precise-Time-Protocol) server is necessary. As some commercially available navigation units do not yet support the output of this format, a 'low-cost' PTP-server can be set up, e.g. by creating the required time information on single board computer like a Raspberry Pi.

4. PROCESSING AND QUALITY

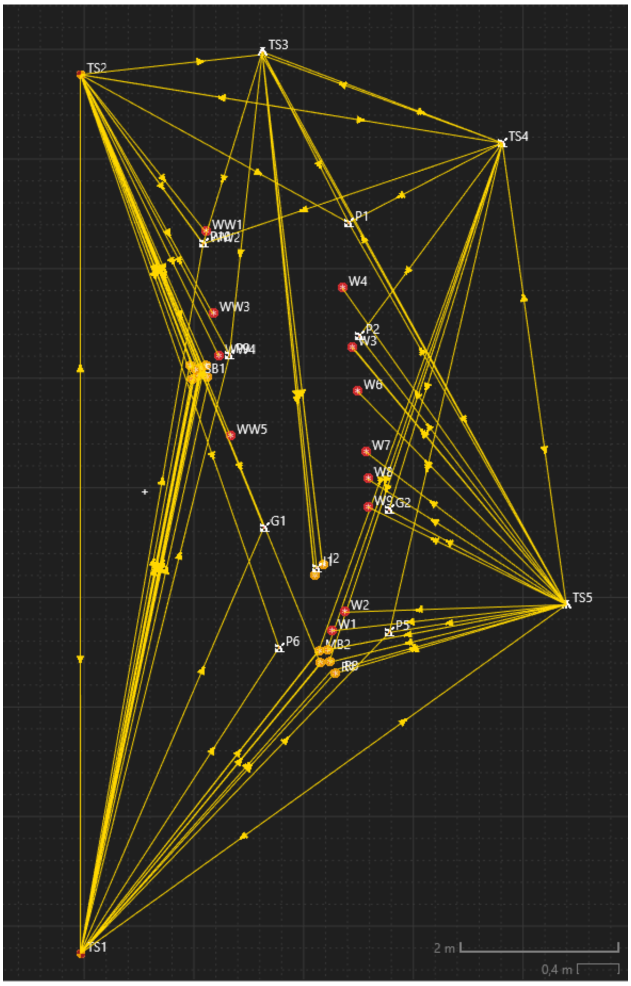

Figure 5: Geodetic network around DVocean (top view), software: Leica Infinity

Figure 6 depicts the observations and the points of the geodetic network. Some additional points (*Wx*) represent a rough estimation of the waterline plane, but are not considered in the described processing procedure. After recognizing and removing outliers, all remaining observations are processed by considering them to be part of an 3D geodetic network. The network adjustment is calculated without constraints, whereby previously determined approximated coordinates are introduced for all measurement points. To make sure that the determined standard deviations for the point coordinates are adequate, the variances of the observation groups (directions, vertical angle and slope distances) have to be adapted by estimating and considering the corresponding variance components. By applying the presented procedure, the processed results of the ship calibration on the HCU surveying vessel DVocean achieve 3D standard deviations of better than the required 5 mm for nearly all measured points: Only two mounting points for a instrument exceeds. In these cases the SMRs were moved between the mounting points and it is assumed to have an unsufficient centering quality of the SMR. However, due to the walls of the cabin and the constraints for the line of sight to measure the fixed points on the IMU housing, the coordinates of these points couldn't be cross checked. The computed standard deviations cannot state the accuracy and reliability of these points.

The adjusted coordinates in the auxiliary, land based coordinate system are now transformated into vessel coordinate system. By using at least three fixed points on the ship as identical points with known coordinates in both coordinate systems, a 3D coordinate transformation can be performed. The transformation parameters are calculated by using theses point coordinates. Traditionally, geodesists use an adjustment model for that purpose, e.g. the Gauß-Helmert model for this purpose (e.g. Koch 2002). More robust approaches are the Least-Median-Square estimator for coordinate transformations (Kanani, 2000), which uses a quaternion based rotation matrix (Shen et al. 2006). Lösler (2011) adapted it for the determination of 3D transformation parameters which is less prone to outliers or deviations in the point coordinates.

5. CONCLUSION

Sonar measurements which are traditionally used in hydrography are nowadays supplemented by optical measurement methods. Especially new time-of-flight based underwater laser scanners offer a very high sampling rate and a potentially higher geometric accuracy of the acquired structures. However, their achievable measurement range is far below that of echo sounders. To benefit from the advantages of the underwater laser scanners in distances of up to several tens of meters, a careful and precise ship calibration including a highly precise time stamp is required. The latter can be solved by using a PTP server. For the determination of the lever arms and especially of the installation or respectively boresight angles of the underwater laser scanner, currently high precision surveying instruments like a laser tracker have to be used. Generally, the lever arm calibration of a hydrographic measurement system can be also performed with a high precision total station in a geodetic network, including a network adjustment.

Since the ship's motion must be compensated in the measured data, the calibration parameters for the motion unit in particular is very important. Especially on small surveying vessels like the HCU owned DVocean, the determination of the lever arms can be challenging because obstacles often interrupt the direct line of sight between a surveying instrument and the marked points on the housing of the IMU. Here, two approaches are presented to solve this problem. Simulations show that even the use of a stick extension can overcome this problem. By attaching a reflector with a very high centering accuracy (e.g. SMR), a geometric precision of 3 mm can be achieved for the hidden point if a sufficient amount of points is acquired. The use of a specially manufactured calibration frame can accelerate the calibration process.

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BIOGRAPHICAL NOTES

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