DEPTH ACCURACY IN SEABED MAPPING WITH UNDERWATER VEHICLES

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Abstract - **The HUGIN II untethered underwater vehicle (UUV) provides detailed seabed survey services to the offshore industry on a commercial basis. This paper discusses the resulting depth accuracy of the digital terrain model (DTM) that can be achieved with an UUV using standard commercially available multibeam echosounders, navigation sensors, pressure transmitters, CTD sensors, sound velocity sensors and international standards for computation of salinity and density. The results are also applicable for remotely operated vehicles (ROV) and towed fish.**

I. INTRODUCTION

Untethered underwater vehicles (UUV) have proved impressive performance in commercial seabed mapping operations both with respect to mapping efficiency and data quality. UUV mission efficiency has been discussed in [1] and [2]. In demanding operations the accuracy of the resulting seabed map is of crucial importance. The digital terrain map (DTM) horizontal position accuracy was investigated in [3]. It was shown that 1.4 m (1σ) positioning accuracy has been achieved in commercial operations with the HUGIN vehicles at 300 m depth and 50 m altitude. This paper addresses the depth accuracy that can be expected in the resulting DTM.

In 1998 HUGIN II was considered used in an operation for surveillance of seabed subsidence due to oil production. If for instance the seabed sinks 10 cm a year, this imposes strict requirements to the instrumentation in order for the seabed subsidence to be observable. In this paper a complete error budget for the depth accuracy is presented and quantified. This work has been done within the framework of the HUGIN development program.

In the HUGIN development program two untethered underwater vehicles have been produced. The vehicles are fitted with a Kongsberg Simrad EM 3000 multibeam echosounder (MBE) for underwater surveys to depths of 600 m. HUGIN I had its first sea trial in summer 1996 and has been used as a test and demonstration platform. HUGIN II was in spring 1998 put into commercial operation, offering services to the survey market. The HUGIN development program is a co-operation between Norwegian Defence Research Establishment (FFI), Kongsberg Simrad AS, Norwegian Underwater Intervention AS (NUI) and Statoil, [1].

II. UUV SEABED MAPPING

The objective of the UUV system is to collect data for seabed mapping. This data will be merged with data collected from the survey vessel and a DTM will be produced in post-processing. Fig. 1 illustrates which data is collected by the HUGIN vehicle and which data is collected by the survey vessel. Post-processing is necessary due to limited capacity on the acoustic links.

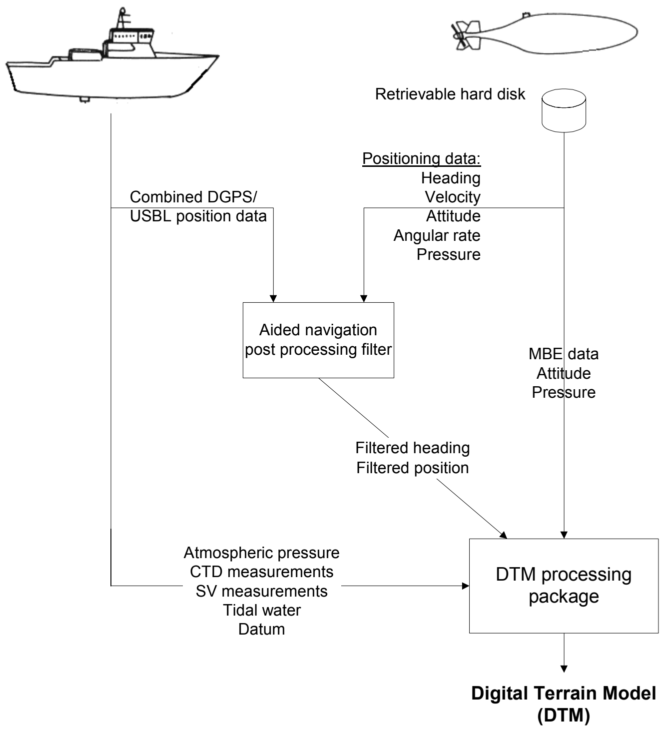

Fig. 1. HUGIN II post-processing scheme

The multibeam echosounder data and the HUGIN navigation sensor data are stored on a hard disk. After a mission the navigation data is merged with the DGPS/USBL position data stored aboard the survey vessel in a Kalman filter based post-processing filter. This filter and its performance are described in [3] and

[4]. The improved heading and position estimates are fed into the software package responsible for producing the DTM. Numerous proprietary and commercial DTM software packages exist. The multibeam echosounder data, attitude data and pressure data are retrieved from the HUGIN hard disk while water level recorder data, CTD data, sound velocity data, atmospheric pressure data and datum have been stored on the survey vessel.

III. ERROR MODELING

The DTM depth is the sum of the UUV depth and combined MBE angle and range measurements. The error sources contributing to the DTM depth error are accordingly grouped into two categories denoted:

- UUV depth
- MBE ensonification

The UUV depth estimate is produced by combining the pressure sensor measurements with a density profile estimate and measurements of tidal water and atmospheric pressure. In order to estimate a density profile, CTD measurements of conductivity, temperature and pressure are needed. The relationship between these quantities and salinity are described by an international standard called the Practical Salinity Scale, 1978 (PSS-78). The density profile can be computed by inputting temperature, pressure and salinity to the International Equation of State of Seawater, 1980 (EOS-80). PSS-78 and EOS-80 have been endorsed by the Joint Panel on Oceanographic Tables and Standards (JPOTS), see [5]. Depth are given by:

$$z = \int_{p_{ATM}}^{p_{UUV}} \frac{1}{\rho(S,t,p)g(L,p)} dp \qquad (1)$$

where z is depth (m), p is pressure (Pa), S is salinity (psu), t is temperature $({}^\circ\mathrm{C})$, L is latitude, $g(L,p)$ is gravity $(\mathrm{m/s^2})$ and $\rho(S,t,p)$ is density $(\mathrm{kg/m^3})$. Numerical solution to the integral in Eq. (1) based on EOS-80 is derived in [6].

In Section IV some of the error analysis have been based on a simplified version of Eq. (1):

$$z = \frac{p_{UUV} - p_{ATM}}{\bar{\rho} g} \qquad (2)$$

where p_{UUV} is UUV pressure sensor reading (Pa), p_{ATM} is atmospheric pressure (Pa) and $\bar{\rho}$ is average density. $\bar{\rho}$ is given by:

$$\bar{\rho} = \frac{1}{p_{UUV} - p_{ATM}} \int_{p_{ATM}}^{p_{UUV}} \rho(S,t,p) dp \qquad (3)$$

Survey vessel mounted multibeam echosounder accuracy is a well exploited field, see for instance [7]. MBE error models for survey vessels apply for UUVs as well.

When discussing error sources, it is important to differ between absolute accuracy and relative accuracy. Absolute accuracy is the accuracy of an estimate compared to its true physical value. Relative accuracy describes the precision of an estimate over time compared to a not necessarily true physical value. For instance in surveying seabed subsidence, the accuracy of an established datum is of lesser importance as long as the same datum is used in all consecutive survey campaigns.

IV. UUV DEPTH RELATED ERRORS

In this section, the most important UUV depth related error sources listed in Table 3 are discussed.

A. Pressure transmitter

HUGIN II is equipped with a Digiquartz 9001K-101 pressure sensor. This sensor has an accuracy specification of 0.01% FS (full scale), FS = 1000 psi (≈700 m), [8]. The screened version 9001K-105-005 with an accuracy specification of 0.005% FS is of interest for applications with strict DTM depth accuracy requirements. Obviously, it is important not to choose a sensor with a higher FS than strictly necessary.

The pressure sensors should be calibrated once a year in a certified laboratory. Qualified laboratories will typically have a dead weight tester (DWT) with an absolute accuracy of 0.005% OR (of reading).

In Table 1 an error budget for Digiquartz 9001K-105-005 is summarized. The pressure sensor is assumed thermalized to the surroundings and recently calibrated. The figures in bold are used for calculating the relative accuracy.

Table 1. Pressure sensor accuracy

Error Source	Specification	Error
DWT accuracy	0.005% OR	0.015 m
RMS residual conformance between pressure sensor and DWT	0.0005% FS	**0.0034** m
Sensor accuracy	0.005% FS	**0.034** m
Transient thermal error	0.01% FS for 20° step	**0** m
Stability per year	0.01% FS	**0** m
Resulting absolute accuracy		0.037 m
Resulting relative accuracy		**0.034** m

B. Water level recorder

The conventional way of measuring tidal water is to place a pressure sensor on the seabed. Thus in principle, we will have similar error budget as the one presented in Table 1. An example of a water level recorder can be found in [9]. Applying this specification we get a depth uncertainty of 0.069 m (1σ) for FS = 1000 psi.

Table 2. PSS-78 and EOS-80 computed density sensitivity to varying CTD errors. The sensitivity has been computed at a nominal working point of *p* = 100 bar, *t* = 5°C, *C* = 3.4 S/m.

CTD error	Temperature sensitivity	Pressure sensitivity	Conductivity sensitivity	Root-squared-summed error
Example: **Expendable CTD** $\Delta p = 5$ dbar, $\Delta t = 0.035^\circ$ C, $\Delta C = 0.0035$ S / m	0.0020	0.0330	0.0319	0.0459
Example: **Good quality CTD** $\Delta p = 0.7$ dbar, $\Delta t = 0.01^\circ$ C, $\Delta C = 0.001$ S / m	0.0003	0.0094	0.0091	0.0131
Example: **Oceanographic research CTD** $\Delta p = 0.1$ dbar, $\Delta t = 0.001^\circ$ C, $\Delta C = 0.0003$ S / m	0.00003	0.0009	0.0027	0.0029

C. Datum

Establishing and relating measurements to a correct datum is a critical task for absolute determination of the seabed level. The accuracy of the tidal datum is dependent upon the deployment time for water level recorders and density measurements. By assigning sufficient deployment time, the datum can be established with an absolute accuracy better than 0.05 m for 300 m water depth, [10]. If an established datum is used throughout the operation and in consecutive surveying campaigns, relative accuracy will not be affected.

D. Density profile

Referring to the description of the steps involved in computing the density profile in Section III, the estimated density profile accuracy is dependent upon:

- CTD temperature measurement accuracy
- CTD pressure measurement accuracy
- CTD conductivity measurement accuracy
- Absolute accuracy of PSS-78
- Absolute accuracy of EOS-80
- Density profile variations in time and space versus the CTD measurement frequency

The absolute accuracy of PSS-78 and EOS-80 is determined by the laboratory measurements used to construct the equations.

By using the simplified formula for pressure to depth conversion in Eq. (2) and modeling the error in estimated average density, $\Delta\bar{\rho}$, and the corresponding depth error, $\Delta z_{\Delta\bar{\rho}}$, we get:

$$z + \Delta z_{\Delta\bar{\rho}} = \frac{p_{UUV} - p_{ATM}}{(\bar{\rho} + \Delta\bar{\rho})g} \qquad (4)$$

Considering the error budget in Table 3, a reasonable requirement $\left|\Delta z_{\Delta\bar{\rho}}\right| < \Delta z_{\Delta\bar{\rho},bound}$ will be $\Delta z_{\Delta\bar{\rho},bouund} = 0.05$ m. This translates to the following requirement on the error in estimated average density:

$$\frac{-\Delta z_{\Delta\bar{\rho},bound}\bar{\rho}^2 g}{p_{UUV} - p_{ATM} + \Delta z_{\Delta\bar{\rho},bound}\bar{\rho} g} < \Delta\bar{\rho} < \frac{\Delta z_{\Delta\bar{\rho},bound}\bar{\rho}^2 g}{p_{UUV} - p_{ATM} - \Delta z_{\Delta\bar{\rho},bound}\bar{\rho} g} \qquad (5)$$

Clearly, increased UUV operation depth means stricter requirements on $\Delta\bar{\rho}$. For instance at 300 m depth we have $\sigma(\Delta\bar{\rho}) < 0.17$ kg / m^3, while at 1000 m depth $\sigma(\Delta\bar{\rho}) < 0.05$ kg / m^3 and at 3000 m $\sigma(\Delta\bar{\rho}) < 0.02$ kg / m^3.

The effect of CTD accuracy on density has been investigated using the Seabird Seasoft Software Package [11]. This software computes density according to the algorithms in [6] which incorporate PSS-78 and EOS-80. Table 2 shows the density sensitivity for three CTD sensors of varying accuracy. The table has been computed by taking the difference between the density determined at nominal C, T, D and at nominal + error. From the table we see that down to 300 m depth, expendable CTD type of specifications are sufficient to meet the 0.05 m requirement, for depths down to 3000 m, the good quality type of CTD is sufficient. The most expensive CTDs intended for oceanographic research are not necessary for meeting the requirements.

In real life the most important error source is likely to be the density profile variations in time and space and the chosen measurement frequency to account for these changes. The survey vessel should have arrangements for continuos CTD measurements of the whole water column throughout the operation.

E. Acceleration of gravity

The effect of the gravity model inaccuracy can be modeled similar to the effect of error in estimated density. However, gravity model inaccuracy does not affect the relative DTM depth accuracy as long as the same model is used in consecutive survey operations.

F. UUV velocity pressure distribution

UUVs have a velocity pressure distribution over the hull. The stagnation pressure p_{SP} at the bow is given by:

$$p_{SP} = \tfrac{1}{2}\rho v^2 \qquad (6)$$

where v is the UUV forward velocity. At 4 knots the stagnation pressure corresponds to 0.2 m. Along the hull, the velocity pressure decreases and close to the maximum diameter the vehicle has its lowest negative pressure, [12]. The effect of the velocity pressure distribution inside a partly perforated water filled hull is hard to predict, but care must be taken in placement of the pressure sensor. In Table 3 we assume a resulting depth uncertainty of 0.05 m (1σ).

G. Surface waves

The dynamic pressure at the UUV due to surface waves and swell has been modeled and analyzed in [13] according to linear wave theory. For a 200 m wavelength the dynamic pressure is negligible for UUV depths larger than 200 m.

V. MBE ENSONIFICATION RELATED ERRORS

In this section, the most important multibeam echosounder related errors listed in Table 3 are discussed.

A. MBE depth accuracy

The depth error of a multibeam echo sounder is dependent upon the signal to noise ratio. Provided a signal to noise ratio above 10 dB, the depth error is in the order of 0.1% of UUV altitude, [7].

B. Seabed topography and soil conditions

In rough seabed topography one might experience depth errors due to averaging effects of the MBE beam footprints. Certain seabed soil conditions can also contribute to depth errors due to acoustic penetration. These effects are assumed negligible in the error budget in Section VI.

C. Sound velocity profile

The sound velocity (SV) profile can be determined in two ways:

1. Computation of sound velocity from CTD data
2. Direct measuring sound velocity probe

The Joint Panel on Oceanographic Tables and Standards has endorsed the Chen and Millero, 1977 equation for describing the SV/CTD relationship [14], [6]. The absolute accuracy of this equation is believed to be in the order of 0.25 m/s. Given the *good quality CTD* specifications in Table 2, it can be shown using the software package in [11], that relative sound velocity uncertainty due to CTD errors is less than 0.05 m/s.

Direct measuring sound velocity sensors with an absolute accuracy specification of 0.06 m/s are commercially available, [15].

As with determination of the density profile, the dominating error source is probably the physical variations in time and space and the corresponding measurement frequency. At the Troll field on the Norwegian continental shelf, changes in sound velocity near the bottom in the order of 2 m/s within the same day has been measured [10].

Zero mean sound velocity measurement noise through the water column will not lead to any significant depth error. A constant measurement error will always give a range error and, in case of beam steering, also an angular error. The following model is given in [7]:

$$\Delta z_{\Delta c} = \frac{\Delta c}{c_0} h(1 - \tan\phi_{beam} \tan(\phi_{beam} - \phi)) \qquad (7)$$

where Δc is the constant measurement error, h is UUV altitude, c_0 is average sound velocity, ϕ_{beam} is MBE beam pointing angle and ϕ is roll. It may be impractical to measure the sound velocity profile from the UUV down to the bottom. If we assume that the sound velocity estimate error is linearly increasing from zero at the UUV to Δc_{bottom} at the bottom, the depth error is given by:

$$\Delta z_{\Delta c_{bottom}} = \frac{\Delta c_{bottom}}{2c_0} h(1 - \tan\phi_{beam} \tan(\phi_{bottom} - \phi)) \qquad (8)$$

Simplifying the model by assuming $\Delta z_{\Delta c_{bottom}} = 0$ and statistically independent error sources, we get:

$$\sigma(\Delta z_{\Delta c}) = \sigma(\Delta c) \frac{h}{c_0} \sqrt{1 + \tan^4 \phi_{beam}} \qquad (9)$$

which is used when calculating the error budget in Section VI.

D. Orientation sensor error

Depth error due to orientation sensor roll error, $\delta\phi$, and pitch error, $\delta\theta$, is given by:

$$\Delta z_{\delta\phi} = h\delta\phi \tan(\phi_{beam} + \phi) + Y\delta\phi + Z\delta\phi^2 \qquad (10)$$

$$\Delta z_{\delta\theta} = h\delta\theta \tan\theta + X\delta\theta + Z\delta\theta^2 \qquad (11)$$

where θ is pitch and X, Y and Z are the UUV body referenced distances between the orientation sensor and the MBE transducer. The last two terms in the equations represent error in lever arm compensation due to roll and pitch error. In normal UUV operation $\Delta z_{\delta\phi}$ will be the dominating error source as an increasing function of MBE beam angle. Typical accuracy of a modern orientation sensor is $\sigma(\delta\phi) = \sigma(\delta\theta) = 0.06°$.

A heading error, $\delta\psi$, causes a MBE footprint positioning error which is an increasing function of MBE beam angle. This positioning error causes a depth error dependent upon the slope angle of the seabed terrain, β:

$$\Delta z_{\delta\psi} = h\delta\psi \tan(\phi + \phi_{beam}) \tan\beta \qquad (12)$$

E. Orientation sensor mounting axis misalignment

Orientation sensor mounting axis misalignment are modeled similar as Eq. (10) and (11). Given the accuracy of modern orientation sensors and navigation systems, sensor mounting axis misalignment may in real life turn out to be the major error contributor unless the mechanical mounting is addressed properly. The HUGIN UUV mechanical production specification is 1 mrad (1σ) in all axis.

F. MBE transducer mounting axis misalignment

Depth error due to MBE transducer mounting axis misalignment in roll, $\delta\phi_{MBE}$, and pitch, $\delta\theta_{MBE}$, is modeled as:

$$\Delta z_{\delta\phi_{MBE}} = h\delta\phi_{MBE} \tan(\phi_{beam} + \phi) \tag{13}$$

$$\Delta z_{\delta\theta_{MBE}} = h\delta\theta_{MBE} \tan\theta \tag{14}$$

VI. ERROR BUDGET

The error sources in Table 3 are assumed statistically independent. Hence, the total depth uncertainty is calculated by root-square-summing the error contributions. Errors contributing to the relative DTM uncertainty are in bold, errors only contributing to absolute DTM uncertainty have normal font. The figures in Table 3 are based on the following parameters: UUV depth 300 m, UUV altitude 50 m, roll 0°, pitch 5°, seabed slope 0°, MBE beam angle 30°.

In Fig 2 the DTM depth uncertainty is shown as a function of MBE beam angle. The DTM depth uncertainty increases with increasing MBE beam angle as a result of the error models for the sound velocity profile, the orientation sensor error, the orientation sensor mounting axis misalignment and the MBE transducer mounting axis misalignment.

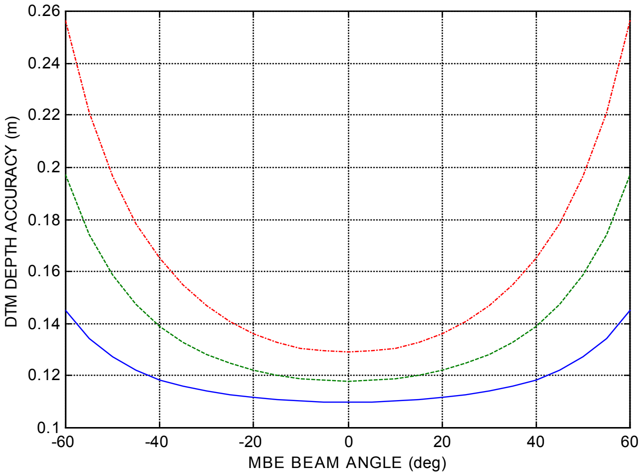

Fig 2. DTM depth uncertainty as a function of MBE beam angle. UUV altitude *h* = 30 m (solid), *h* = 50 m (dashed), *h* = 70 m (dash-dot).

VII. RECOMMENDATIONS FOR ENSURING HIGH DTM DEPTH ACCURACY

To counteract the physical variations of seawater properties in time and space, the survey vessel should have arrangements for continuos CTD and sound velocity measurements of the water column.

Higher accuracy can be obtained by averaging. Given *n* independent measurements of the same physical quantity, it can be shown that the standard deviation of the average estimate is inverse proportional to the square root of *n.* Averaging can be achieved by either adding redundant sensors (redundancy is also beneficial from a UUV reliability point of view) or having overlap in the survey lines. An alternative to redundant sensors is use of screened sensors, if available from the manufacturer. Screened sensors are more expensive but have higher accuracy than standard sensors.

Special consideration should be taken to minimize mounting axis misalignment of navigation and orientation sensors and transducers.

The UUV altitude and the degree of survey line overlap should be chosen according to the DTM depth accuracy specifications.

VIII. CONCLUSIONS

UUVs with a standard sensor outfit have the potential of collecting data for high quality seabed mapping.

A complete DTM depth error budget has been identified. Modeling and quantification of the individual error sources reveals that a DTM depth accuracy of 0.13 m (1σ) can be achieved for 300 m UUV depth, 50 m altitude and 30° MBE beam angle (see Fig 2). This DTM depth accuracy is provided that all UUV and survey vessel sensors perform according to specifications and that the seabed topography is flat and there is no MBE beam penetration in the seabed.

The processing of a DTM is a complex task involving fusion of a large set of sensor data of different character and stepwise execution of complex algorithms. Thus, in a survey operation it is essential to verify the DTM depth accuracy that is actually achieved by a thorough examination of real data. A real data verification is also required for confirming the set of assumptions made in this paper when deriving the DTM depth accuracy estimate.

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Table 3. Contributing error sources for resulting DTM depth uncertainty. Errors contributing to the relative DTM uncertainty are in bold, errors only contributing to absolute DTM depth uncertainty have normal font.

Error source	DTM depth uncertainty	Basis for depth uncertainty calculations
UUV depth		
Pressure transmitter	**0.034** m (1σ)	Pressure sensor accuracy: 0.005% FS, FS = 1000 psi.
Datum	0.05 m (1σ)	See Section IV.C.
Water level recorder	**0.069** m (1σ)	WLR accuracy: 0.01% FS, FS = 1000 psi.
Atmospheric pressure	**0.01** m (1σ)	Barometer accuracy: 1 hPa (1σ).
Density profile	**0.05** m (1σ)	See Eq. (5), $\sigma(\Delta\bar{\rho}) < 0.02$ kg / m^3 .
Acceleration of gravity	0.1 m (1σ)	See Section IV.E.
Pressure to depth conversion	0.1 m (1σ)	Formula accuracy stated in [6].
UUV velocity pressure distribution	**0.05** m (1σ)	See Section IV.F.
Pressure sensor position mounting accuracy	**0.005** m (1σ)	HUGIN mechanical mounting specification.
Surface waves	**0.0** m (1σ)	200 m wavelength and UUV depth > 200 m.
MBE ensonification		
MBE depth accuracy	**0.05** m (1σ)	MBE depth accuracy: 0.1% of UUV altitude.
Sound velocity profile	**0.02** m (1σ)	See Section V.C, $\sigma(\Delta c) = 0.5$ m/s.
Seabed topography	**0** m	See Section V.B.
Seabed soil conditions	**0** m	See Section V.B.
Orientation sensor error	**0.03**m (1σ)	See Section V.D, $\sigma(\delta\phi) = \sigma(\delta\theta) = 0.06°$, $\beta = 0°$.
Orientation sensor mounting axis misalignment	**0.03**m (1σ)	1 mrad (1σ) HUGIN mechanical mounting specification .
MBE transducer mounting axis misalignment	**0.03** m (1σ)	1 mrad (1σ) HUGIN mechanical mounting specification .
MBE transducer position mounting accuracy	**0.005** m (1σ)	HUGIN mechanical mounting specification.
UUV positioning error	**0** m	Slope angle of seabed terrain $\beta = 0°$.
Time synchronization error	**0** m	Slope angle of seabed terrain $\beta = 0°$.
Resulting relative DTM depth uncertainty		
Bold figures root-square-summed	**0.13** m (1σ)	MBE beam angle: $30°$.

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