Assessment of Approaches for Converting Acoustic Echo Intensity into Suspended Sediment Concentration

POERBANDONO, Indonesia and Roberto MAYERLE, Germany

Key words: suspended sediment concentration, hydro-acoustic, ADCP backscatter, optical beam transmissometer.

SUMMARY

In this paper, approaches for converting acoustic echo intensity from an acoustical profiler into suspended sediment concentration are discussed. Comparison of estimated concentration of sediment in suspension from a 1200kHz Direct Reading Broadband Acoustic Doppler Current Profiler (ADCP) and an optical beam transmissometer are presented. Data are collected during field measurements from a moving vessel in tidal channels of the German North Sea Coast. The ADCP was installed downward whereas the optical beam transmissometer was simultaneously lowered. Both devices gave measurement over the water column. Echo intensity strengths recorded by the ADCP are converted to suspended sediment concentration using an empirical equation. The equation is developed on the basis of linear relationship between logarithm of concentration and echo intensity. The constants are found using simple regression analysis. It is found that the concentration from converted acoustic echo intensities are within a good agreement with those obtained from the optical beam transmissometer. A tendency of underestimation and increasing of discrepancy with the increase of concentration magnitude are identified. However, the approach is independent to the location of measurements, current velocity magnitude and water depth. These results encourage the use of acoustical profiling for monitoring fine suspended sediment transport.

SARI

Makalah ini mendiskusikan pendekatan-pendekatan untuk mengubah intensitas gema menjadi konsentrasi sedimen tersuspensi. Perbandingan hasil estimasi konsentrasi sedimen dalam suspensi yang diperoleh dari pengukuran menggunakan *Acoustic Doppler Current Profiler* (ADCP) dan *optical beam transmissometer* akan disajikan. Pengukuran lapangan dilakukan di Pantai Utara Jerman dari kapal yang bergerak. Saat pengukuran berlangsung, ADCP dioperasikan dengan menghadap ke bawah. Pada saat yang bersamaan, *optical beam transmissometer* diturunkan dari kapal. Dengan cara ini pengukuran sepanjang kolom air menggunakan ke dua alat itu dapat dilakukan. Intensitas akustik yang direkam ADCP diubah menjadi konsentrasi sedimen tersuspensi menggunakan persamaan empirik yang dibangun berdasarkan hubungan linier antara intensitas gema dan logaritmik dari konsentrasi. Tetapan-tetapan regresi diperoleh dari analisis regresi sederhana. Perbandingan hasil estimasi konsentrasi sedimen tersuspensi menggunakan ke dua alat tersebut memperlihatkan hasil yang cenderung sama. Hasil pengukuran akustik cenderung lebih rendah dan perbedaannya cenderung sebanding dengan konsentrasi. Walaupun demikian, pendekatan ini

memperlihatkan ketaktergantungan pada lokasi pengukuran, kecepatan arus dan kedalaman. Hasil ini menunjukkan kemampuan alat akustik untuk memantau angkutan sedimen.

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1. INTRODUCTION

Measurement of sediment transport plays an important role in monitoring coastal and harbour environment. Recent development in hydro-acoustic technology allows application of versatile devices for non-intrusively sensing suspended sediment concentration using Acoustic Doppler Current Profiler (ADCP). Within past decade ADCPs have been indeed widely used to measure water current velocity profile. The working principle is based on the transmission of acoustic pulses of known frequency from ADCP transducers to the water column. Sound scatterers (i.e. suspended sediment; assumed to move with the same speed of current velocity) in the layer being measured reflect the echo back to the transducer. As the sound scatterers relatively move further or closer to the ADCP, the echo is Doppler shifted proportionally. The current velocity with respect to the ADCP can accordingly be determined from the shifted frequency.

ADCPs also provide echo strength data from the water layer being measured. It is usually termed as acoustic echo intensity or acoustic backscatter. Initial study of the use of acoustic backscatter for estimating suspended sediment concentration with qualitative evaluation has been done by, for example, Schott & Johns [1987], Flagg & Smith [1989] and Heywood et al. [1991]. Approaches for converting acoustic backscatter into suspended sediment concentration based on empirical technique were also proposed by Young et al. [1982], Vincent et al., [1986] and Hanes et al. [1988]. Extended elucidation of backscatter theory of ADCP signal and the conversion of echo intensity into suspended sediment concentration are given in Libicki et al. [1989] and Thorne & Hardcastle [1991]. Based upon their elucidation Holdaway et al. [1999] has comprehensively reviewed and applied the conversion of echo intensity into suspended sediment concentration. The concentration of suspended sediment is assumed to be directly proportional to acoustic intensity (voltage recorded by the ADCP) and logarithmically proportional to acoustic attenuation due to water and sediment concentration. The conversion approach was applied in a field experiment using a 1MHz ADCP system.

Results comparable with an independent optical beam transmissometer were obtained.
Application of such an approach requires direct calibration at a measuring layer to determine a proper attenuation constant. Once the constant is determined, calculation of sediment concentration at each layer in the water column is carried out using iteration since the concentration obtained from the first calculation step will be used to determined attenuation constant for the next one. Although the results are very promising but the working sequence is quite laborious. Some other parameters (e.g. water and sediment properties) must be adequately known. Additionally, accurate measurement for attenuation coefficient due to water absorption is needed. Furthermore, special setting should be developed to obtain

directly the measured voltage from the transducer. Such a complication makes the application of the conversion approach less practical.

2. MATERIAL AND METHODS

2.1 Conversion Approach

Approaches for converting acoustic echo intensity into suspended sediment concentration are still in the development stage and face major difficulties due to complicated interaction between sediment properties and sound waves. However, practical conversion approaches are available and commonly based on empirical method assuming proportionality of suspended sediment concentration and either absolute echo intensity value or echo intensity increment. In this instance, it is commonly assumed that echo intensity is inversely proportional to depth and directly proportional to density of the scattering layer. It also depends on backscatter coefficient and transmitted power [Gordon, 1996].

2.1.1 ADCP Backscatter Data

During its propagation in the water, acoustic waves experience geometrical spreading and attenuation due to water masses and the presence of suspended sediments. This results in the so-called transmission loss (*TL*). If the rate of attenuation (α) is assumed to be constant over the entire depth, transmission loss of sound wave propagation can be expressed as [RD Instruments, 2000]:

$$TL = 20\log_{10}R + 2\alpha R \qquad (1)$$

in which, $20\log R$ = loss due to geometrical spreading, $2\alpha R$ = loss due to attenuation, α = rate of attenuation due to water and sediment and R = distance from ADCP transducer to the layer being measured. ADCP transducers receive echo intensity in count unit. This is termed as Reflected Signal Strength Indicator (RSSI) [Deines, 1999; Simpson, 2001]. Conversion of RSSI from count to dB unit is done in the post processing using software provided by the manufacturer considering transmission loss (*TL*) and echo intensity scale (K_C) which is temperature dependent. Default ADCP configuration commonly assumes that α and K_C values are constant through the entire depth. The ADCP backscatter data is obtained by [RD Instruments, 2000]:

$$EI = IK_C + TL \qquad (2)$$

in which, EI = echo intensity in dB unit and I = echo intensity in count unit.

2.1.2 Equations for Converting Echo Intensity into Suspended Sediment Concentration

In the post processing ADCP echo intensity data have been corrected from errors due to attenuation and distance-normalised. Based on this simplified theoretical background and practical use of ADCP backscatter data, Deines [1999], SonTek [2002], Patino & Byrne [2001] and Gartner [2002] recently proposed practical application of approaches for converting echo intensity into suspended sediment concentration. Two different types of empirical conversion approaches can be distinguished:

$$10\log_{10}(c/c_r) = K.\Delta EI \quad (3)$$
$$10\log_{10}(c) = A.EI + B \quad (4)$$

in which, EI = echo intensity, EI_r = echo intensity at the reference level, c = suspended sediment concentration, c_r = suspended sediment concentration at the reference level, K = proportionality constant and A and B = regression slope and intercept. The first type (Eq. 3) is based on the proportionality of echo intensity increment ($\Delta EI = EI - EI_r$) with the logarithm of the concentration ratio [e.g. Deines, 1999; SonTek, 2002]. The second type (Eq. 4) is based on linear relationship between the logarithm of concentration and echo intensity [e.g. Patino & Byrne, 2001; Gartner, 2002].

2.2 Domain and Devices

In order to test the applicability of the conversion approaches, measurements were carried out in tidal channels of the German North Sea Coast. In the investigation domain, the water depth varies between 5 and 20m. The tide is semi-diurnal and has a mean range of around 3m. During spring tide, the maximum depth-averaged tidal current velocity in the location of measurements is around 1m/s. Flood currents move generally to the East whereas ebb currents move to the West. The bed sediments consist mainly of very fine to fine sands having median sizes ranging from 80 to 230µm. Sediments moving in suspension have been found to be much finer. It has median sizes of ranging from 6 to 86µm. Recent investigation indicates a uniform distribution of suspended sediment concentration over the water column [Poerbandono et al., 2003].

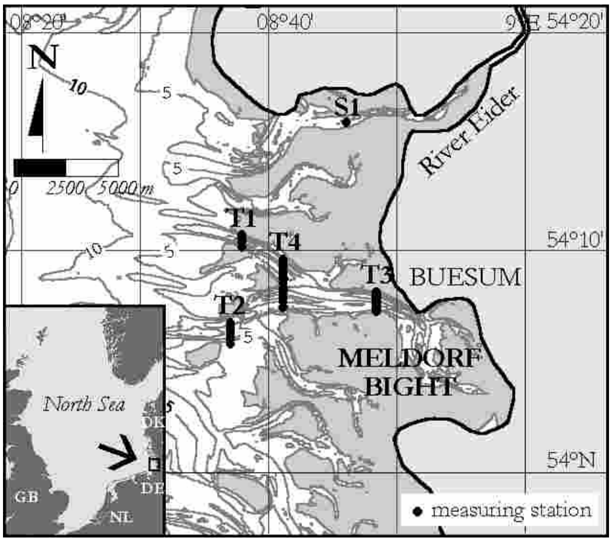


Figure 1: Measuring locations in the investigation domain

Two main devices were deployed. A 1200kHz Broadband Direct Reading ADCP was installed downward-looking from a research vessel. The recording was set to be 12s for each ensemble (measuring column) and 0.5m bin (measuring layer). Simultaneously an optical beam transmissometer was lowered by a winch and collected data at 0.2m vertical resolution. It gives relative measure (in %) in terms of optical transmission. This optical measurement was calibrated using around 200 direct samples of suspended sediment concentration. The calibration provided a calibration curve to convert optical transmission values to suspended sediment concentration. Independent comparison of optically measured suspended sediment concentration from the optical beam transmissometer against direct sampling concentration showed that most of data (about 90%) lie within a factor of 2. Further assessment confirmed the accuracy of optical measurement of about 30% [Poerbandono, 2003]. List of test activities with the corresponding measuring location, date, data volume and approaches tested are chronologically given in Table 1.

Table 1: List of test activities

Test number	Measuring location(s)	Date	Number of stations	Approach(es) tested	Remark
1	T1, T2 and T3	March, June, September and December 2000	201	Deines [1999] (Eq. 3)	Poerbandono & Mayerle [2003]
2	T3 and S1	September 2001 and May 2002	205	Deines [1999] (Eq. 3), SonTek [2002], Patino & Byrne [2001] and Gartner [2002] (Eq. 4)	Lu [2003] and Poerbandono [2003]
3	T3 and T4	June 2001	345	Gartner [2002] (Eq. 4)	This paper

2.3 Evaluation of Empirical Conversion Approaches

Poerbandono & Mayerle [2003] have carried out test of conversion approach proposed by Deines [1999] (see: Table 1, Test No. 1). It examined the use of Eq. 3. In the corresponding study it was found that the proportionality constant (K) is equal to 0.45. The results confirmed the agreement between acoustical and optical measurement of within a factor of 2. In addition to that, later on, Lu [2003] carried out preliminary test of application of approaches proposed by Deines [1999] (using different set of field data), SonTek [2002], Patino & Byrne [2001] and Gartner [2002]. Evaluation of these approaches is given in Poerbandono [2003] (see: Table 1, Test No. 2). The results confirm that approaches proposed by Deines [1999] and Gartner [2002] show better results with respect to those shown by approaches proposed by SonTek [2002] and Patino & Byrne [2001]. Further discussions of approaches proposed by Deines [1999] and Gartner [2002] are given herein.

2.3.1 <u>Evaluation of Approach Proposed by Deines [1999] (Eq. 3)</u>

For converting echo intensity into suspended sediment concentration, application of Deines approach [Deines, 1999] requires reference concentration. The reference concentration should be obtained from an independent measurement at a certain depth. In this instance, measurement from an optical beam transmissometer can be considered. It should be applied for every single measuring column. The test had shown that the best results were obtained by locating reference concentration at mid depth. About 97% of the data analyzed in the test resulted within a factor of 2 with respect to those estimated on the basis of optical measurements [Poerbandono & Mayerle, 2003]. Lu [2003] also confirmed similar results.

This can be considered quite good bearing in mind that the accuracy of the optical device with respect to the mechanical sampler showed only 90% of the values are within a factor of 2 (see: Section 2.2). Although the results are also independent to the location of measurements, magnitude of current velocity and suspended sediment concentration and water depth but the application of such approach is found to be less practical.

2.3.2 Evaluation of Approach Documented by Gartner [2002] (Eq. 4)

Conversion approach documented by Gartner [2002] (Eq. 4) requires calibration of backscatter data using direct sampling concentration. The calibration is carried out on the basis of linear relationship between logarithm of concentration and echo intensity. The constants can be found using simple regression analysis. Treatment and analysis of direct sampling concentration are usually laborious. However, independent relation between acoustical and optical data at a measuring column makes this conversion simpler, since no reference concentration required and the calibration can be done using different set of data.

2.3.3 Comparison of Approaches Proposed by Deines [1999] and Gartner [2002]

Preliminary test and comparison of the application of conversion approach proposed by Deines [1999] and Gartner [2002] have been given in Lu [2003] and the evaluation is given in Poerbandono [2003]. It was found that independent backscatter calibration as documented in Gartner [2002] gives comparable results with respect to those given by Deines [1999]. The average data lying within a factor of is 96% and the average relative error is found to be 24%. Table 2 summaries the corresponding evaluation.

Table 2: Comparison of approaches proposed by Deines [1999] and Gartner [2002]

	Measuring locations			
	T3		**S1**	
Approaches	**Data within a Factor of 2**	**Relative Error**	**Data within a Factor of 2**	**Relative Error**
Deines [1999] (Eq. 3)	93%	31%	100%	10%
Gartner [2002] (Eq. 4)	88%	35%	100%	21%

2.4 Independent Backscatter Calibration

Further assessment of independent calibration of backscatter data is carried out here. The calibration is done by comparing echo intensity value against direct sample concentration obtained at the same depth of a measuring column. Figure 2 shows regression line correlating direct sample concentrations and echo intensity data. The concentration is expressed in mg/l.

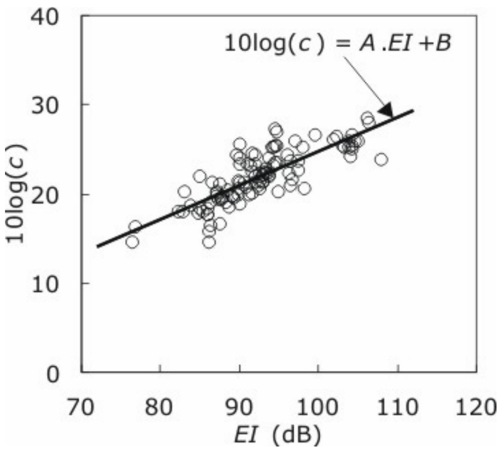


Figure 2: Calibration of backscatter data using direct sample concentrations

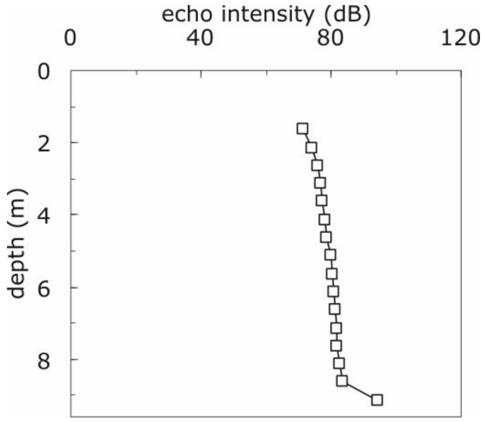
The direct sample of suspended sediment concentration was obtained at 1m heights above seabed using trap sampler. Gravimetric analysis of suspended sediment concentration was carried out following procedure documented in van der Linde [1998]. The range of direct sample concentration was between 0.03 and 0.7kg/m^3, whereas, the range of echo intensity data was between 76.4 and 107dB. Eq. 4 is used to relate echo intensity and direct sample concentration data. Simple regression analysis is used to find the regression slope (A) and regression intercept (B). The corresponding analysis employs 105 data pairs. It is found that A and B are respectively 0.38 and –13.57. The correlation coefficient (r^2) is found to be 0.81.

3. RESULTS AND DISCUSSIONS

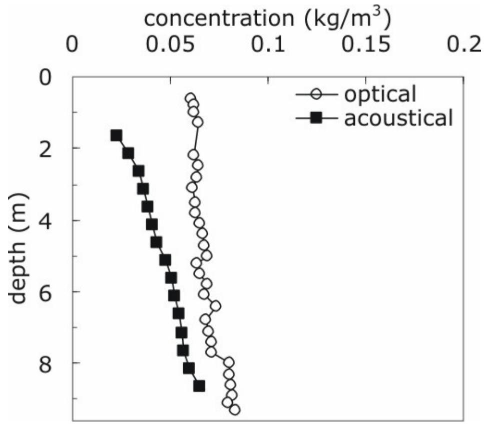
The method for calibrating backscatter data presented in the previous section (see: Section 2.4) is validated using different data set from the same domain. In the corresponding validation, data from 345 profile measurements obtained from T3 and T4 are used. Over 5000 data pairs are involved.

3.1 Measurement Data

Backscatter data recorded from ADCP represent the density of the scattering layer of a measuring column. It is also highly effected by the presence of seabed since the seabed usually has much higher density than the layer of sediment in suspension. Therefore, the reflected acoustic signal from the last measuring layer (the closest bin to the depth) cannot be used since it is influenced by strong reflection from the seabed. It leads to a very high echo intensity value. Close to the transducers (the first measuring layer; the closest bin from the transducers), backscatter data tend to be weaker. Such a tendency can be identified since the vertical profile of backscatter data usually exhibit extreme gradient at the second bin. This is due to ADCP transient time for transmitting and receiving signal. Similar finding was also reported by Birch et al. [1999] and Lane et al. [1999]. For the application of the test documented in this paper, backscatter data from the first and the last bins were eliminated. Typical example of measurement data and the comparison of suspended sediment concentration profiles obtained from optical and acoustical measurements are shown in Figure 3.



(a) Example of backscatter profile



(b) Example of optical and acoustical con-centrations at a measuring column

Figure 3: Typical example of backscatter profile data and a comparison of suspended sediment concentration profiles

The example shown in Figure 3 is taken from a measuring station of T4-South. The water depth is 9.6m, the depth-integrated velocity is 0.65m/s and the depth-integrated concentration obtained from the optical device is 0.067kg/m^3. The average relative error is 31% and about 93% of data are within a factor of 2.

3.2 Performance Evaluation

The performance of the conversion approach is evaluated by comparing the estimated suspended sediment concentration from the ADCP against those obtained from the measurement using optical transmissometer of each measuring layer (ADCP bin). It is found that the comparison shows a good agreement between acoustical and optical concentration data. In average, about 93% of data pairs are within a factor of 2. Accordingly, the average relative error is about 31% and the average absolute discrepancy is 0.03kg/m^3. This result confirms a comparable performance with respect to those shown by measurement using an acoustical beam transmissometer (see: Section 2.2). Summary of the test results classified by measuring location is shown in Table 3.

Table 3: Test results

Date	Location	Number of Stations	Number of Data Pairs	Data within a Factor of 2	Relative Error
21 June 2001	T4-North	97	1225	94%	33%
21 June 2001	T4-South	84	1083	94%	31%
22 June 2001	T3	76	1364	99%	23%
28 June 2001	T3	88	1335	86%	36%

3.3 Other Influencing Factors

Additional investigation is carried out to examine the dependency between the discrepancies with some possible influencing factors. In the investigation, the relative errors are related to the measuring transect, measuring station, water depth, depth-averaged velocity and depth-averaged concentration (from the optical measurement). It is found that major discrepancies tend to occur at higher concentration. It has also found that the acoustical estimation of depth-averaged concentration tends to be underestimated. Figure 4 shows comparison of depth-averaged optical and acoustical concentration in kg/m^3.

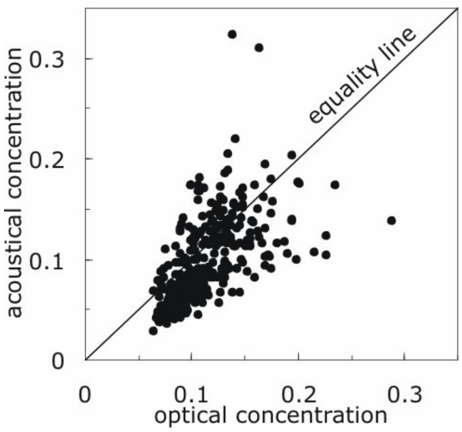


Figure 4: Comparison of depth-averaged optical and acoustical concentration in kg/m^3

Further investigation confirms that there is no strong dependency of discrepancy due to the variations of measuring transects, measuring stations, water depths and depth-averaged velocities.

4. CONCLUSIONS

In this paper, empirical approaches for converting acoustic echo intensity from an acoustical profiler into suspended sediment concentration have been discussed. Results from comparison of estimated concentration of sediment in suspension from a 1200kHz Direct Reading Broadband ADCP and an optical beam transmissometer are presented. Echo intensity strengths recorded by the ADCP were converted to suspended sediment concentration using an empirical equation. The equation is developed on the basis of linear relationship between logarithm of concentration and echo intensity. The constants are found using simple regression analysis.

It is found that the concentration from converted acoustic echo intensities are within a good agreement with respect to those obtained from the optical beam transmissometer. About 93% of data pairs are within a factor of 2. Accordingly, the average relative error is about 31% and the average absolute error is 0.03kg/m^3. A tendency of underestimation and increasing of discrepancy with the increase of depth-integrated concentration magnitude are identified.

However, the approach is independent to the location of measurements, current velocity magnitude and water depth. These results encourage the use of acoustical profiling for monitoring fine suspended sediment transport. It should be noted that the applicability of the approach is restricted for a condition with very fine sand sediment, range of concentration of between 0.03 to 0.7kg/m^3, water depth of up to 20m and almost uniformly distributed concentration profile.

ACKNOWKLEDGEMENT

Field data were collected within the research project Prediction of Medium-term Coastal Morphodynamics (*Prognose mittelfristiger Küstenmorphologieänderungen* - PROMORPH) [PROMORPH, 2003]. The project was funded by the German Ministry of Education and Research (*Bundesministerium für Bildung und Forschung* - BMBF). The authors thank working colleagues at the Research and Technology Centre (*Forschungs -und Technologiezentrum* - FTZ) of the Christian Albrechts University of Kiel, Germany for their notable involvement during measuring campaigns.

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BIOGRAPHICAL NOTES

Dr.rer.nat. Poerbandono completed doctoral degree in Coastal Geosciences and Engineering from Christian Albrechts University of Kiel, Germany in December 2003 and is currently instructor at the Hydrography Working Group of the Department of Geodetic Engineering, Faculty of Civil Engineering and Planning, Institute of Technology Bandung, Indonesia.

Prof. Dr. Roberto Mayerle is civil engineer. He is professor in geoscience and currently head of the Coastal Research Laboratory and director of the Research and Technology Centre at the Christian Albrechts University of Kiel, Germany.

CONTACTS

Poerbandono
Hydrography Working Group, Department of Geodetic Engineering,
Faculty of Civil Engineering and Planning, Institute of Technology Bandung
Jalan Ganesha 10
Bandung 40132
INDONESIA
Tel. + 62 22 2530701 3678
Fax + 62 22 2530702
Email: poerbandono@gd.itb.ac.id
Web site: http://laut.gd.itb.ac.id

Prof. Dr. Roberto Mayerle
Coastal Research Laboratory, Research and Technology Centre,
Christian Albrechts University of Kiel
Otto-Hahn-Platz 3
24118 Kiel
GERMANY
Tel. + 49 431 8803641
Fax + 49 431 8807303
Email: rmayerle@corelab.uni-kiel.de
Web site: http://www.corelab.uni-kiel.de