Acoustic Tomography as a Remote Sensing Method to Investigate the Near-Surface Atmospheric Boundary Layer in Comparison with In Situ Measurements

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20 June 2001 and 20 February 2002

ABSTRACT

The acoustic tomography method is applied in the atmospheric surface layer to observe near-surface temperature fields. Important advantages of this technique are the remote sensing capacity and the possibility of directly deriving area-average meteorological quantities.

Combined observations of the air temperature using an acoustic tomography system and point measurements were carried out to validate the tomographic method. Results were used to compare representativeness for a designated area of direct measurements with the tomographic solution.

The results demonstrate agreement between the two different measurement methods, except for some deviations of absolute values mainly caused by an imperfectly sheltered and ventilated thermocouple device.

1. Introduction

Sound waves propagate through the atmosphere with different sound velocities, according to the air temperature and wind vector fields influenced by the environmental conditions. Therefore, acoustic parameters characterizing the sound propagation bear information and lead to a spatial description of atmospheric properties.

This approach has been used since the early twentieth century to probe the vertical structure of the atmosphere in connection with powerful explosions and investigations of audible zones (cf. Ostashev 1997; Wilson et al. 2001).

The possible application of sound propagation in the lower atmospheric boundary layer for acoustic travel time tomography was verified by Spiesberger and Fristrup (1990), as well as Wilson and Thomson (1994). Recently, Spiesberger (1999) demonstrated tomographic localization of moving sound sources (calling blackbirds).

Acoustic tomography is defined in this study as a combined measurement and data analysis technique to reconstruct a slice through the atmosphere using the reaction of the atmospheric layer to the external sound energy. The measured response of the atmosphere to the acoustic wave is called projection data. Tomographic image reconstruction methods operate on these projection data to create a cross-sectional picture.

In the present study, measured travel time values of sound signals between different transmitters and receivers were used as initial line-integrated values to derive spatially averaged meteorological quantities. The acoustic rays should cover all parts of the observational site and have a quite uniform spatial distribution. Because each measurement contains information on the properties of the atmospheric layer through which the sound wave propagates, a tomographic inverse algorithm provides a spatial mapping of meteorological quantities.

Acoustic tomography describes the opposite situation to the traditional forward problem. From values of measured quantities one can use mathematical inverting techniques to derive an estimation of the values of system parameters that explain or reproduce the experimental observations. The directly resulting spatially averaged meteorological quantities are useful for the preparation and analysis of measuring campaigns as well as for the evaluation of model output data, such as large eddy simulations (Wyngaard and Peltier 1996). Such model-consistent, spatially representative data could be conventionally provided by point measurements followed by an interpolation procedure, assuming designated relations between different points.

Remote sensing methods yield data directly from a volume, an area, or along a line. Acoustic travel time tomography belongs to the last group of methods, main-
ly characterized by the high accuracy compared to other remote sensing methods and by the construction of horizontal slices through the atmosphere (Ziemann 2000). It is possible to provide information on the representativeness of point measurements and the homogeneity of measurement sites using acoustic tomography. Together with a conventional data survey one can derive the validity of well-known turbulence theories, which normally require horizontal homogeneity regarding the mean meteorological quantities (Raabe et al. 2002). An open question, which will be investigated in this study, is the comparison of tomographically obtained and conventionally derived point data.

The following section describes the acoustic tomography method and its applicability to measurements in the atmospheric boundary layer. In contrast to the studies by Spiesberger and Fristrup (1990), Wilson and Thomson (1994), and Spiesberger (1999), the applicability of an alternative tomographic algorithm will be demonstrated to detect absolute values of meteorological quantities without additional information about the reference state of the atmosphere. Furthermore, the characteristics of a thermo electric temperature measurement device are briefly explained. These sheltered and ventilated thermocouples were used to evaluate the tomographic temperature observations.

In sections 3 and 4, an overview to the observations on a test site at the Meteorological Observatory Lindenberg (Germany) and the accompanying experimental results is presented. The comparison between remote sensing (tomography) and point (thermocouples) data constitutes the main content. In the last section, the results are summarized, and an outlook to further investigations is supplied.

2. Spatial-averaging and point measurement methods

a. Inverse reconstruction technique

Under the assumption of small Mach numbers (ratio of wind speed to sound speed), the acoustic travel time of a signal between a fixed transmitter and a receiver can be expressed as

\[ \tau = \int_{ray} \frac{dl}{c_{eff}}, \]  

where \( dl \) is the element of the arc length along the propagation path, and \( c_{eff} = c_z(T_w) + v \cdot \mathbf{r}' \) symbolizes the effective sound speed with the coupled influence of the virtual acoustic temperature \( T_w \) (\( c_z \) is Laplace’s sound speed) and the wind vector \( \mathbf{v} \) component in the direction \( \mathbf{r}' \) of the sound propagation (Munk et al. 1995). Because of this connection between acoustic and meteorological quantities, it is possible to derive the air temperature and wind speed by means of acoustic travel time tomography.

The coupled influence of the virtual acoustic temperature and the wind vector on the sound speed is a difficulty, if one would like to obtain the temperature field. One possible solution is described in Arnold et al. (2001).

A difficulty in the numerical application of the tomographic method is the dependence of the ray path itself on the unknown distribution of the effective sound speed; therefore, the line integral [Eq. (1)] becomes non-linear in this quantity. Straight lines connecting the sound source and the receiver are used to approximate the true ray path to avoid this difficulty. The error made by this approximation was qualitatively investigated by sensitivity tests with a sound-ray model including a generalized equation of refraction (cf. Ziemann et al. 1999b, 2000). A more quantitative estimation of this error was provided by Ziemann et al. (2001) using vertical measurements of temperature and wind speed gradients at the Lindenberg test site (see section 3a). In summary, the straight-line approximation can be applied if we use pathlengths of sound rays not more than a few hundred meters over a relatively homogeneous surface, and if moderate vertical temperature and wind gradients are present. The validity of this approximation should be investigated if one applies the method with greater transmitter–receiver distances or at very small heights above the ground, where the vertical gradients of temperature and wind speed are significantly stronger.

The measurements of travel time are always discrete and finite in number. In the usually applied discrete-data/discrete-solution approach, the medium is divided into grid cells, and the aim of the inversion is to estimate the associated parameter values (sound speed and thus temperature) inside the grid cells (Munk et al. 1995; Wilson and Thomson 1994).

In the case of travel time tomography, one has to solve the inverse problem to get the spatially averaged sound speed depending on the virtual acoustic temperature. There are several possible algorithms to solve the linear equation system, for instance, iterative algebraic reconstruction techniques, which were developed for applications in seismic tomography (Gilbert 1972) and for medical uses (Herman 1980). Another possibility is the stochastic method, which was used for atmospheric tomography (Spiesberger and Fristrup 1990; Wilson and Thomson 1994; Spiesberger 1999). A survey of the features of different inverse methods for acoustic tomography is presented in Ziemann et al. (1999a).

Iterative algebraic reconstruction techniques, which are based on the method of least squares, minimize the sum of quadratic differences between the modeled and the measured travel time. In contrast to that algorithm, the stochastic inverse methods look for a solution under the presupposition that each single difference between the estimated and the true reciprocal sound velocity is minimized (Munk et al. 1995). This requires knowledge of the reference state of the atmosphere, use of additional measurement equipment, and, in addition, turbulence parameters to describe the correlation between
model parameters and measurements. With the use of straight-line sound rays and an iterative algebraic reconstruction algorithm it is possible to derive absolute values of the temperature without additional information, in contrast to stochastic reconstruction algorithms, which were used by Spiesberger and Fristrup (1990) and Wilson and Thomson (1994) in the atmospheric surface layer.

There are a large number of iterative reconstruction techniques that could be successfully applied to inversely solve Eq. (1). In particular, the simultaneous iterative reconstruction technique (SIRT) is characterized by stable convergence for datasets with measuring errors, by nonsignificant developments of artifacts, and simple handling during online evaluation (see Humphreys and Clayton 1988; Ziemann et al. 1999a). A comprehensive survey of the mathematical background of SIRT and other iterative algebraic reconstruction techniques is given by van der Sluis and van der Vorst (1987).

All inverting algorithms follow a similar scheme. An initial guess of the slowness values in the grid cells is derived from a simple backprojection of the measured travel time data into grid cells using the inverse of Eq. (1) (after discretization). By means of the obtained reciprocal sound speed one can apply forward modeling [Eq. (1) after discretization] to get a modeled travel time. Now the difference between the experimentally obtained and the simulated travel time values is provided by the model. After backprojection of this difference, and adding a resulting correction to the present model, an updated version of the simulated travel time follows. This iterative improvement of the modeled data is continued until attainment of a convergence criterion. The process leads to area-average values of temperature $T_{av}$.

### b. Accuracy of the tomographic measurement

The accuracy of travel time determination and the tomographic analysis has been described by Arnold et al. (1999, 2001), Raabe et al. (2002), Ziemann (2000), and Ziemann et al. (1999a,b, 2001). Consequently, only a survey of those results is presented here.

The travel time measurements, as well as the determination of the distances between sources and receivers, have to be carried out with a high degree of accuracy. Thus, the average source–receiver distance of ray paths going through one grid cell should be greater than 150 m to guarantee a high enough accuracy for the travel time determination. Moreover, the accuracy of the path-length measurements between transmitter and receiver plays a significant role in the reconstruction algorithm. The results of sensitivity tests with the SIRT model confirmed the insensitivity of the algorithm with regard to small variations of the transmitter and receiver positions up to $\pm 5$ cm.

In summary, with an actual travel time accuracy $\Delta \tau$ of about $\pm 0.3$ ms and a source–receiver distance determination $\Delta l$ around $\pm 5$ cm, the horizontal temperature field can be obtained with an accuracy of $\pm 0.5$ K for one time step, according to the error propagation law $\pm \Delta T_{av} = \pm [(\Delta l \partial T_{av}/\partial l)^2 + (\Delta \tau \partial T_{av}/\partial \tau)^2]^{1/2}$. A substantial decrease of the measurement error is possible if the single measurements are temporally or further spatially averaged. For example, if the error of a single measurement amounts to 0.5 K, then the error in the temperature difference between two grid cells, averaged over 20 values, is $\sqrt{2}(0.5)/\sqrt{20} \approx 0.2$ K.

Furthermore, the quality of the tomographic reconstruction has to be checked for each specific tomographic array (cf. Ziemann et al. 2001). To summarize, the SIRT algorithm allows the derivation of absolute temperature values without additional information or measurements of the initial values of the investigated meteorological quantity. The error contributed by the tomographic reconstruction algorithm itself is less than the error caused by the travel time and ray path determination. The high requirements concerning the accuracy of travel time and ray path determination are a disadvantage of this procedure in comparison to measurements of relative changes in relation to a known reference state (Wilson and Thomson 1994).

### c. Construction and accuracy of validation measurements

To validate the acoustically determined temperature, simultaneous in situ measurements with a thermoelectric device were carried out. For this purpose, fast-response thermocouples with thin wires are suitable (Schienbein and Arnold 2001). The active junction of this measurement device consists of iron–constantan braid wires to minimize the response time and the heat transfer. The resulting sensor has a length of 5 cm and a diameter of 0.4 mm, giving a fast response of 2 s in a calm atmosphere. To avoid the influence of direct shortwave radiation, the sensor tube is sheltered by a ventilated (2.2 m s$^{-1}$) Young shelter. A connecting wire transfers the electric signal to the junction that is located with a Pt100 thermometer inside an aluminium cylinder filled with wax. The datalogger records the data from the Pt100 and the thermoelectric signal and calculates the actual air temperature. Samples are taken at 1 Hz, and averaged temperature values are stored every 30 s.

The inertial behavior of the ventilated Young shelter was investigated as a first step to estimate the measurement error and the response time of the thermocouple (Schienbein and Arnold 2001). The heat transfer from the airstream to the sensor and the heat conduction from the (tube) mount to the sensor play an important role. It was determined that the inertial time range is not constant. This behavior leads to a time delay of the response time with a magnitude of some minutes. Because the radiation shelter is imperfect, the temperature measurements during direct radiation differ from the measurements by remote sensing methods (e.g., sonic thermometer) up to 1.5 K.
The next step was the investigation of the self-heating caused by ventilation influencing the temperature sensor. In the laboratory (without wind influence) the temperature difference with and without this heat source amounts to 0.3 K. Under wind influence (wind tunnel) the temperature difference between the ventilated and the unventilated thermocouple diminishes if the wind speed is larger than 2.5 m s$^{-1}$.

To sum up the results of Schienbein and Arnold (2001), the calibration of this thermoelectric device led to the result that double-wall shelters with a high-grade polished surface as well as a ventilation of 3 m s$^{-1}$ are necessary to sufficiently reduce errors by direct sunlight and a self-heating caused by ventilation.

3. Observations at the Lindenberg test site

a. Test site

Several experimental studies using the introduced tomographic measurement and analysis system were carried out (e.g., Arnold et al. 1999, 2001; Raabe et al. 2002; Ziemann et al. 1999a,b, 2001). The comparison between the area-average tomographic data and point measurements using fast-response thermocouples will be discussed in the following. For this purpose the tomographic array was built up at the Boundary Layer Research Site (52°10'02"N lat, 14°07'34"E lon, 73.1 m ASL) near the German Weather Service Meteorological Observatory at Lindenberg, which is located in Brandenburg, Germany, 70 km southeast of Berlin and 290 km south of the Baltic Sea. Lindenberg has a continental climate (Adam et al. 1997). The mean yearly sum of precipitation is 563 mm, the air temperature mean is 8.6°C, and the most frequent wind direction is west-southwest (time period 1961–90). Nearly homogeneous surface conditions were found over a wind direction sector from south to northwest and over distances of at least 500 m. The land use of the surrounding area (20 km × 20 km) is dominated by forests (42%), agricultural fields (41%), lakes (6.5%), meadows (5%), villages (3.5%), and other (2%). The surrounding area exhibits a moraine landscape with heights above sea level between 40 (Spree River) and 120 m, which is typical for large parts of northern central Europe south of the Baltic Sea (Beyrich 2000).

The tomographic array (see Fig. 1) was established at the Lindenberg site, mainly on the borders of the Boundary Layer Research Site (nearly homogeneous grassland, vegetation height 3–5 cm). The source-receiver path S4 to R2 was oriented north–south (see Fig. 1). On the western side the tomographic array, with a horizontal dimension of 200 m × 240 m, extended past...
the micrometeorological measurement site by 50 m. Hence, the measurements were also influenced by a tangled stubble field. The vegetation height agreed with the height of the grassland, so the surface conditions could be treated as relatively homogeneous.

b. Experimental design

Six transmitters (compression drivers) and five receivers (microphones) were positioned on tripods at a height of about 2 m (see Fig. 1). The speakers and microphones must be placed in such a way that one is able to distinguish between the travel times of different transmitters at any single receiver, because all signals had the same form (no signature, 1000-Hz pulse). Thirty travel times (number of transmitters times number of receivers) of acoustic signals resulted at any moment. The term “moment” means a finite duration of nearly 1 s corresponding to the largest source–receiver distance of about 280 m. The measurements were repeated every 30 s. Details of the experiment and the technical devices are described by Arnold et al. (2001).

The spatial resolution of the measured field mainly depends on the number of sound rays (number of transmitters and receivers), the size of the tomographic array, the accuracy of the travel time measurements, and the differences between the sound speed values at different points inside the measuring area (e.g., Ziemann et al. 1999a, 2001). Ultimately, we could apply a grid cell size of 50 m × 50 m, apart from at the borders (see Fig. 1).

To derive the air temperature $T$ depending on $T_w = T(1 + 0.51q)$, (2)

the specific humidity $q$ has to be included in the calculations. Assuming a horizontal temperature gradient of 1 K (100 m)$^{-1}$, a value of the specific humidity of 0.005 kg kg$^{-1}$, and using the derivative of Eq. (2), the humidity gradient begins to play an important role if it reaches at least 0.005 kg kg$^{-1}$ (100 m)$^{-1}$, a rather unrealistic case. Hence, the horizontal variability of the specific humidity is of minor relevance, and humidity measurements of the German Weather Service Linden-berg at only one point were used to calculate the air temperature $T$.

To validate the acoustically determined temperature, simultaneous in situ measurements with a thermoelectric device were carried out (see section 2c). The air temperature was obtained at four different points inside the tomographic array (T1–T4, Fig. 1). These sheltered temperature sensors were calibrated so that the deviations between them were substantially smaller than 0.1 K (under the same environmental conditions).

The analyzed measurement period was characterized by the following weather situation: a weakening influence of high pressure, an optimal insolation during the morning hours, and a daily temperature variation of more than 10 K. The mean wind speed was 3.5 m s$^{-1}$ from the southwesterly direction.

The temperature and wind profiles showed the following daily course. The air temperature was nearly height-independent at sunrise and sunset. During the daytime hours, the vertical temperature decrease strengthened up to the late morning and reached amounts up to 0.4 K m$^{-1}$ at a height of 2 m. Before and after the time of sunrise and sunset, respectively, the temperature increased in height, and the absolute gradient reached a maximum of 0.5 K m$^{-1}$. The wind speed gradient was relatively constant during day and night (0.2 m s$^{-1}$ m$^{-1}$). From 0800 UTC to noon the wind speed gradient slightly increased, up to an amount of 0.3 m s$^{-1}$ m$^{-1}$ at a height of 2 m.

The mostly sunny development on the investigated day was only interrupted by a thunderstorm with show- ers in the early afternoon. The tomographic measure- ments were broken off during this period because the microphones are not really waterproof. More information on the daily sequence of global shortwave radiation and the wind speed can be found in Figs. 2 and 5, respectively.

4. Results and discussion

a. Tomographically derived values of temperature

With the adjusted travel time data (removed wind influence), area averages of the air temperature at a height of 2 m were calculated with one value for each grid cell. Figure 2 shows an example of the spatial variability of the tomographically derived air temperature. The maximum and minimum values of the air temperature at one moment inside the tomographic array (30 grid cells) are mapped. The temperature values are smoothed by averaging over a time interval of 10 min (20 values).

In addition to the general temperature trend, shown in the daily sequence of the air temperature, one can detect spatial differences of the air temperature. The maximum difference amounts to 1.5 K and mainly occurs during the day under convective conditions. These spatial differences and the temporal temperature fluctuations could be caused by coherent structures, which are known to play an important role in the dynamics of turbulent flows in the near-ground atmosphere (Wilson et al. 2001). If the horizontal dimensions of such organized inhomogeneities are comparable to the tomographic array, then the moving structures cause resolvable variations of meteorological quantities such as air temperature. Because the periodicity of the time series of tomographic data around noon agrees well with that derived by the point measurements (see Fig. 2), one may conclude that these variations are not stochastic but rather are caused by organized structures. Furthermore, the temporal alterations of all temperature results coincide, except for a time delay, with the general energy...
Fig. 2. Ten-min averages of air temperature derived from the tomographic inversion [max (solid squares) and min (open circles) of 30 grid cells] and measured by thermocouples [max (solid line) and min (dotted line) of four points], as well as 10-min averages of global shortwave radiation (diamonds) on 24 Sep 1999 at the Lindenberg site.

Fig. 3. Comparison of the spatial averages of air temperature derived from the tomographic inversion (averaged over 30 grid cells) and measured by thermocouples (averaged over four points) on 24 Sep 1999. The optimal agreement (1:1 line) is only attained under the condition of absent direct sunlight.

input (see global radiation Fig. 2), a possible confirmation for the connection with coherent structures during the day. However, a continued data analysis must clarify this behavior by including an investigation of the night hours.

b. Comparison of spatially averaged data with point measurements

As already mentioned, the temperature course agrees well between the tomographic method and the point measurement (Fig. 2). But there is also a systematically quantitative difference between the two methods. The comparison of averaged grid cell values (spatially averaged over grid cells 7, 9, 22, and 24) with the averaged values measured by thermocouples (spatially averaged over T1, T2, T3, and T4) for the study day in September results in an obvious overestimation of the temperature during the day by the in situ measurements in relation to the acoustic tomography (see Figs. 2 and 3). The main reason for this behavior is the influence of shortwave radiation on the thermoelectric device, even though the thermocouples are built in ventilated radiation shields (see section 2c). This behavior leads to a maximum difference between the remote sensing and the direct methods of 1.5 K during the day. Another cause is the inertia of the Young shelter. If direct shortwave radiation is absent, during night and cloudy sky conditions, the differences are noticeably smaller. Differences under these conditions are caused by the self-heating (ventilation) of the thermocouple device (section 2c). Because the wind speed before sunrise and after sunset is less than 2 m s\(^{-1}\), the ventilation heating leads to slightly higher temperature values measured by the thermocouples. To compare the temporal variability of the time series, the following temperature difference (deviation from the averaged value) was calculated:

\[
 T' = T - \frac{1}{20} \sum_{i=9}^{19} T_i. \tag{3}
\]
In Fig. 4 the daily sequence of these fluctuations is shown. The principal agreement between the two time series of temperature fluctuations is noticeable. A higher variability occurs during the day under convective conditions. The amplitudes of fluctuations \( T' \) are rather small under conditions of a well-mixed atmosphere.

The last comparison between spatially averaged and point measurements was carried out using spatial temperature differences. In Fig. 5 one can see two time series of spatial differences of the air temperature measured by the thermocouples and derived by tomography. The thermocouples T2 (grid cell 9) and T3 (grid cell 24) were located at the stubble field, and the thermocouples T1 (grid cell 7) and T4 (grid cell 22) were located at the grassland site. Sometimes one can determine a qualitatively good agreement between the two methods, when they have the same sign of the difference. This result especially occurs for the difference \( T(T4) - T(T2) \). It may be concluded that this temperature difference was only marginally influenced by the measurement method during the day with a moderate wind speed. The temperature over the grassland site is slightly lower than the temperature over the stubble field. A decoupling between the time series occurs during weak-wind conditions. Compared with this result there is sometimes a disagreement in the signs of the differences, especially for the difference \( T(T3) - T(T1) \) during the day. One reason could be the different wind influence on the two measuring methods. Because this difference was measured in the mean wind direction, it is possible that the tomographic method with its spatially averaging effect is more influenced by the compensating wind effect than are the thermocouples. The tomographically measured temperature over the grassland site is more influenced by the temperature conditions over the stubble field in comparison to the separated point measurements. This behavior could lead to the different spatial temperature gradients observed.

Also, the overall small values of the temperature differences must be recognized. The spatial temperature differences are sometimes of the same magnitude of the measurement error. Thus, universal conclusions from the determined spatial gradients are rather inappropriate.

5. Conclusions and outlook

The comparison between the tomographic temperature measurements and the temperature values derived by ventilated and sheltered thermocouples demonstrates the agreement in the principal daily sequence of absolute values and, in particular, of temporal temperature fluctuations. Nevertheless, one has to recognize differences that are caused by differences of the physical measurement principles, different measurement strategy (temporal and spatial averaging), and the variable data quality that depends on atmospheric and environmental conditions.

Because of the substantial agreement between the tomographic and the thermocouple data, the direct point
measurements are considered as spatially representative to some extent and are hence applicable for micrometeorological investigations over the examined area, but with some known disadvantages, such as the influence of direct sunlight. To increase the certainty of the spatial representativeness, remote sensing methods such as acoustic tomography should be combined with direct point measurement methods, even over rather inhomogeneous surfaces.

Furthermore, the agreement between the two methods indicates the applicability of acoustic tomography for various investigations in the atmospheric surface layer. Operational use of the tomographic method in, for example, monitoring of meteorological test sites, appears possible.

Important questions in this context are the study of the energy balance influenced by inhomogeneities and the study of coherent structures. The principal ability of the acoustic tomography to investigate coherent structures was explained by Kallistratova et al. (2001). One problem is still the differentiation between the influence of such a moving coherent structure and the influence of an inhomogeneous surface. An averaging time of about 1 h should exclude the influence of such organized structures, but the relevant timescales of atmospheric flow perturbations are mostly below this value.

Nevertheless, we have successfully used the tomographic data for the investigation of the horizontal variability of the temperature field (Raabe et al. 2001) to explain the effect of natural inhomogeneity on the energy balance closure. With these data it should be possible to develop objective measures of the degree of homogeneity and to test experimentally such measures (see, e.g., Panin et al. 1998; Zilitinkevich and Calanca 2000). Such investigations could be an important step toward verifying and quantifying the effects of microscale inhomogeneities of natural surfaces on flux measurements at a point and the determination of the energy balance of an area.

Acknowledgments. We would like to thank F. Weiße and M. Engelhorn, as well as S. Schienbein, for their support in the development and manufacturing of the tomographic system and the fast-response thermocouples, respectively. Furthermore, we acknowledge the staff of the German Weather Service Observatory Lindenberg, especially F. Beyrich, as well as the students from the Leipzig Institute for Meteorology. We wish to thank the two reviewers and K. Goldberg for helpful comments and suggestions.

This material is based upon work supported by Deutsche Forschungsgemeinschaft under Grant Ra 569/4-1 and Ra 569/4-1 and by Sächsisches Staatsministerium für Wissenschaft und Kunst (HWP).

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