Optical long slit velocities and a combined optical and H I velocity field for the barred spiral galaxy NGC 1365^{*}

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Abstract. — Optical emission line velocities in NGC 1365 are presented along 35 slit positions, of which 18 have not been published earlier. Diagrams of emission line velocities as function of distance along the slits are presented, and separate velocity fields are derived for the disc as given by the low excitation lines, combined with H I 21 cm VLA data, and for the nuclear outflow cone as given mainly by the high excitation lines. An algorithm for creating a velocity field and contour maps based on measurements along randomly oriented spectrograph slits is given in the Appendix. Detailed discussions and interpretations of these velocity fields are given elsewhere. The combined optical and 21 cm disc velocity field is available by an anonymous ftp.

Key words: galaxies: active — galaxies: individual NGC 1365 — galaxies: kinematics and dynamics — galaxies: spiral

1. Introduction

NGC 1365 is one of the more impressive barred galaxies in the sky. Photographs of this galaxy have been published e.g. by Sandqvist et al. (1982), Laustsen et al. (1987 plate 4) and Sandage & Bedke (1988 p. 42). A three colour mosaic CCD image of the bar region of the galaxy has been published by Jörsäter & Lindblad (1989). A high resolution H I image of the galaxy has been presented by Jörsäter & van Moorsel (1995, hereafter JvM). NGC 1365 is probably associated with the Fornax cluster (Jones & Jones 1980; see also Laustsen et al. 1987 plate 3). With a recent determination of a modest distance to the Fornax cluster of 17 Mpc (Ford 1994), the diameter of NGC 1365 of 11 arcmin would correspond to 54 kpc. It is a supergiant galaxy and has been classified as type SBb(s)I by Sandage & Tammann (1981).

There are several reasons for making this galaxy the prime target in a project investigating the kinematics of barred galaxies. Besides that the galaxy is relatively nearby and can be studied at fairly high resolution, it has a strong bar with prominent dust lanes along its front side as well as an intricate pattern of wisps across the bar. The spiral structure is nearly bi-symmetric with strong

and regularly shaped arms. Its plane of symmetry has an inclination to the line of sight that is favourable for kinematic studies, and there is no obvious satellite galaxy that can perturb the dynamics.

The kinematics of the nuclear region of NGC 1365 seems to have been first investigated by Burbidge & Burbidge (1960) and Burbidge et al. (1962). Lindblad (1978) on the basis of observations obtained with the ESO 3.6 m telescope, combined with those of Burbidge & Burbidge (1960), concluded that within 7'' from the nucleus there exists a rapidly rotating nuclear disc in nearly circular rotation.

The early optical long slit observations, made with image tubes and the Boksenberg Image Photon Counting System (IPCS; Boksenberg 1978) at ESO and combined with image tube long slit observations by C. Peterson at the Cerro Tololo Inter-American Observatory, were published by Jörsäter et al. (1984a). This material was further analyzed by Jörsäter (1984), who derived a rotation curve and a velocity field for the disc and demonstrated the different kinematics of the stellar component and the gas in the bar region, where the latter showed a rather strong velocity gradient, or shock, across the dust lane along the bar. Large deviations from circular motion were found in the nuclear region just outside a nuclear distance of 7''. The shock-like behaviour over the dust lanes along the bar and across a spiral arm was further exemplified by

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^{*}Based on observations made at the European Southern Observatory (ESO), La Silla, Chile

Lindblad & Jörsäter (1987), based on the present material.

Teuben et al. (1986), using the TAURUS scanning Fabry-Perot interferometer on the ESO 3.6 m telescope in the H α line, derived a velocity field for the ionized hydrogen gas in the disc. The velocity field was smoothed to a resolution of 5'' in the nuclear region and 15'' in the spiral arm region. This velocity field shows very similar trends as that of Jörsäter (1984) but with an improved spatial coverage. A high spatial resolution velocity field over the nuclear region was drawn by Lindblad & Jörsäter (1987).

Already our first image tube spectra across the nucleus secured with the ESO 3.6 m telescope in 1977 showed that H α has an underlying broad component. This was soon thereafter confirmed by observations with the Image Dissector Scanner on the Boller & Chivens spectrograph (Véron et al. 1980; Alloin et al. 1981), and the nucleus could be classified as of type Seyfert 1.5, seen through several magnitudes of visual absorption.

Phillips et al. (1983) discovered that the [O III] λ 5007 emission line has two components in some regions surrounding the nucleus. As one of several explanations they suggested a bipolar hollow conical outflow. Jörsäter et al. (1984b) did not resolve the line split but confirmed the difference between high and low excitation velocity fields, and suggested outflow of the high excitation gas from the nuclear region. Edmunds et al. (1988), using the TAURUS, identified one of the split line components with the disc and one with a bipolar outflow and mapped two velocity fields for the [O III] λ 5007 line.

In the present measurements, the two components of the [O III] λ 5007 line are well resolved over parts of the circumnuclear region. One of the components shows similar velocities as H β and other low excitation emission lines that define what we will here call the 'disc' component of the velocity field. The other component corresponds to the bipolar outflow of hot gas from the nucleus, and we will here refer to it as the 'cone' component because of its apparent shape. A combined narrow-band picture of the [O III] outflow cone and the H α hot spot structure in the nuclear region as well as velocity fields for the disc and cone components in that region have been presented by Jörsäter & Lindblad (1989).

NGC 1365 has been mapped in H I with the Very Large Array (VLA) by Ondrechen and van der Hulst (Ondrechen 1985; Ondrechen & van der Hulst 1989). High resolution H I observations of NGC 1365, using multiple arrays at the VLA, have been carried out by JvM who, including the data of Ondrechen & van der Hulst (1989), present a thorough discussion of the H I morphology and velocity field. These observations are complementary to the present ones, as they give an almost complete coverage of the galaxy outside the bar region. CO (1–0), (2–1), and (3–2) line observations with the SEST are presented by Sandqvist et al. (1982, 1995) and Sandqvist (1996).

This paper contains observations, reduction procedure and measured radial velocities for 19 long slit spectra obtained with CCD detectors. Radial velocities for 11 additional spectra obtained at an earlier occasion with IPCS detector have also been replotted here. This data is the basis for the analyses by Hjelm & Lindblad (1996) and Lindblad et al. (1996), where detailed modelling and comparisons with general observations of NGC 1365 have been done.

In order to present a comprehensive velocity field for the disc, the present velocities and velocities from seven long slit spectra obtained by C.J. Peterson have been combined with the H I observations by JvM, using an algorithm presented in the Appendix.

2. Observations

The observations presented here have been carried out during the years 1983 to 1993 with the Boller & Chivens intermediate dispersion long slit spectrographs equipped with CCD detectors and attached to the ESO 3.6 m, the ESO/Max Planck Society 2.2 m, or the ESO 1.5 m telescopes on La Silla, and we replot velocity measurements from observations carried out in 1981 with the ESO 3.6 m telescope equipped with the Boller & Chivens spectrograph and University College London Image Photon Counting System (IPCS). Included in the compilation of the velocity fields are also observations in 1978 and 1979 by C.J. Peterson with the Cerro Tololo Interamerican Observatory (CTIO) 4 m telescope and spectrograph plus Carnegie image tube. The IPCS and CTIO observations have been presented in detail by Jörsäter et al. (1984a). The ESO image tube spectra presented by Jörsäter et al. have not been used here because they have been surpassed by the new CCD data.

Data for the CCD observations are given in Table 1. The columns present in order, the year of the observing run, the ESO telescope used, spectral region (where "blue" refers to the region covering H β to [O III] λ 5007 and "red" the region from [N II] λ 6548 to [S II] λ 6731), slit width in arcseconds, pixel size in microns, dispersion after calibration in Å/pixel, and scale along the slit in ''/pixel.

Table 1. Spectral parameters for the different observing runs

Year	Tel (m)	Spectral region	Slitw. (")	Pix.size (μ)	Disp. (Å/pxl)	Scale (''/pxl)
1983	3.6	blue	2.5	30	0.8	1.14
1984	3.6	blue	2.5	22	0.6	0.85
1984	3.6	red	2.5	22	1.3	0.85
1985	3.6	blue	2.1	30	0.8	1.14
1988	2.2	red	2.0	15	0.86	0.88
1993	1.5	blue		15	0.95	0.86
1993	1.5	red		15	1.90	0.84

Table 2. Identifications and slit positions for CCD spectra

Spectral region	Nr.	Ident.	Ref. point	PA (deg.)	Exp. (min.)	Date
Blue	1	n:225	nucleus	225	120	1983 Nov. 30
	2	n:246	nucleus	246	20	1983 Nov. 30
	3	n:275	nucleus	275	120	1983 Dec. 2
	4	n:302	nucleus	302	120	1984 Oct. 24
	5	n:318	nucleus	318	120	1985 Dec. 17
	6	n:328	nucleus	328	120	1983 Dec. 1
	7	L1:180	H II reg. L1	180	70	1983 Dec. 1
	8	L1:332	H II reg. L1	332	112	1983 Dec. 2
	9	L2/L3:337b	H II reg. L2+L3	337	60	1993 Nov. 13
Red	9	L2/L3:337r	H II reg. L2+L3	337	60	1993 Nov. 13
	10	n:335	nucleus	335	60	1988 Nov. 30
	11	L4:0	H II reg. L4	0	120	1988 Nov. 29
	12	*D:353	star D	353	120	1988 Nov. 29
	13	*E:286	star E	286	60	1988 Nov. 30
	14	*E:309	star E	309	120	1984 Oct. 25
	15	*E:345	star E	345	70	1988 Dec. 2
	16	*E:358	star E	358	120	1988 Dec. 2
	17	*F:323	star F	323	105	1984 Oct. 25
	18	*F:355	star F	355	120	1988 Nov. 30

Details about each of the CCD spectra are given in Table 2. The slit has always been placed over an identifiable reference point (given in the fourth column) which is either the nucleus, an H II region (L and number) or a star (* and letter). In this way there remains no ambiguity in the slit positions. The position angle of the slit, counted from North over East, is given in the fifth column. The reference point is the zero point of the scale along the slit in all figures given here, except for the spectrum 28(*B:19), and the distance scale along the slit is increasing in the direction given by the position angle in the fifth column. A spectrum will be identified by the code [ref.p.]:[pa] as given in the third column. The identification code for the H II regions (L-numbers) are the same as those used by Alloin et al. (1981) and Sandqvist et al. (1982).

The coordinates of the nucleus of NGC 1365 as measured with the ESO Optronics machine from ultraviolet and H α ESO 3.6 m plates via an ESO Quick Blue Survey Schmidt plate, which also contains a number of Perth standard stars, are

$$\alpha = 3^{\text{h}} 31^{\text{m}} 41^{\text{s}}.802 \quad \delta = -36^{\circ} 18' 26''.55 \quad (1950).$$

The positions of the other reference points were measured simultaneously. Their offset positions in arcseconds from the nucleus are given in Table 3.

We want to use a similar identification system for the IPCS spectra of 1981 presented by Jörsäter et al. (1984a). Table 4 gives the slit positions as well as new and old identifications for these spectra.

Figure 1 shows all the positions where velocity measurements have been done plotted on top of optical images of NGC 1365.

3. Data reduction

The wavelength calibration and a geometric correction of the spectra in the dispersion direction was based on MIDAS (Munich Image Data Analysis System) routines using the He Ar spectra exposed before and after the object frames. The calibration procedure for the 1983 – 85 observations was designed and carried out by Santos-Lleó (1986). The calibration was performed over sets of 9 scanlines. The polynomial used was generally of the third degree. In the calibration of the 1988 and 1993 spectra a procedure designed by Hjelm (1994) was used. A row-by-row method was applied and the polynomials were of the third degree. The reduction of the IPCS spectra has been described by Jörsäter et al. (1984a).

Table 3. Offset coordinates for reference points

Ref. point	$x = -\Delta\alpha \cos \delta$ ($''$)	$y = \Delta\delta$ ($''$)
nucleus	0	0
H II reg. L1	-4.38	1.63
H II reg. L2	4.59	-5.42
H II reg. L3	5.67	-2.84
H II reg. L4	-16.56	16.39
H II reg. L29	57.56	78.07
H II reg. L32	-37.58	24.00
H II reg. L33	-29.07	19.40
star B	-159.52	43.13
star D	62.63	13.25
star E	33.10	71.21
star F	-53.15	-147.16

Before putting all the slits together to a velocity field, a velocity-bias, constant for each slit, has to be corrected

Fig. 1. Positions of velocity measurements along the slits drawn on top of an optical image of NGC 1365. The units on the axes are arcseconds

Table 4. Identifications and slit positions for IPCS spectra

Spect. region	Nr.	Ident.	Ref. point	PA (deg.)	Old ident.
Blue	19	n:0	nucleus	0	T361
	20	n:2	nucleus	2	T271519
	21	L2:90	H II reg. L2	90	T24311
	22	L29:0	H II reg. L29	0	T451417
	23	L32:0	H II reg. L32	0	T27510
	24	L33:0b	H II reg. L33	0	T36347
Red	24	L33:0r	H II reg. L33	0	T4511
	25	n:138	nucleus	138	T459
	26	*F:0	star F	0	T4513
	27	*B:0	star B	0	T455
	28	*B:19	star B	19	T453

for. This was done in an iterative manner using all the spectra where the slit crosses at least one other slit. The spectrum 27(*B:0) and the CTIO spectrum F-1324, that are not well tied to the others by crossing points, have not been included in the derived velocity field.

When checking the night sky lines in the object frames after the correction it was found that they were still slightly bent. This is probably caused by the different paths of the light rays when obtaining object frames and when obtaining the arc frames. This could be corrected for, using the night sky lines, but it was decided that, in the region of interest, the effect is not significant. The largest bending, after calibration, of the night sky lines corresponds to a velocity error of 6.5 km s^{-1} . From wavelength calibrated arc spectra, we estimate the error in the

wavelength of the He Ar lines to be less than 3 km s^{-1} and this is compensated for in the velocity-bias correction.

4. Results

The radial velocities of the various emission lines as measured with Gaussian fits along the different spectral slits are presented in Fig. 2. The velocities shown are not corrected for bias. The abscissa in all plots shows the distance along the slit in arcseconds, increasing in the direction of the position angle with the reference point as origin. The different lines measured in each spectrum are indicated in the plot.

In some cases the lines are split and two components have been measured with the Gaussian fitting procedure. The split lines occur in the circumnuclear region and are mostly the higher excitation lines [O III] $\lambda\lambda 4959, 5007$, or [Ne III] $\lambda 3868$. When these higher excitation lines are split, one component is seen to agree in velocities with the lower excitation lines, and constitutes the ‘disc’ component. The other component, that here is interpreted as originating in a nuclear outflow cone, is referred to as the ‘cone’ component. In the spectrum 10(n:335) the lower excitation lines $H\alpha$, [N II] $\lambda 6583$, and [S II] $\lambda\lambda 6716, 6731$, and in spectrum 7(L1:180) the $H\beta$ line, are split too. In this case one of the components follows the disc field and the other the cone field. The CTIO velocities all refer to the disc component and are plotted by Jörsäter et al. (1984a).

In order to create a velocity field from measurements along the scattered slits, a program was developed that uses Fourier series to interpolate between data points. This program, designed by JH, is described in Appendix A. The

Fig. 2. a) Radial velocities as a function of distance along the slit. The zero point of velocity is +1630 km s⁻¹. The reference point and position angle is given by the code number on top. Increasing distance is in the direction of the position angle

Fig. 2. b) Radial velocities as a function of distance along the slit. The zero point of velocity is $+1630 \text{ km s}^{-1}$. The reference point and position angle is given by the code number on top. Increasing distance is in the direction of the position angle

Fig. 2. c) Radial velocities as a function of distance along the slit. The zero point of velocity is $+1630 \text{ km s}^{-1}$. The reference point and position angle is given by the code number on top. Increasing distance is in the direction of the position angle

Fig. 2. d) Radial velocities as a function of distance along the slit. The zero point of velocity is $+1630 \text{ km s}^{-1}$. The reference point and position angle is given by the code number on top. Increasing distance is in the direction of the position angle

Fig. 2. e) Radial velocities as a function of distance along the slit. The zero point of velocity is $+1630 \text{ km s}^{-1}$. The reference point and position angle is given by the code number on top. Increasing distance is in the direction of the position angle

spatial resolution of the velocity measurements along the slit is very high where the line intensity is sufficient, while the separation between slits or groups of measurements can be large. The algorithm for deriving the velocity field then necessarily introduces some smoothing of the velocities along the slits. The resulting velocity field for all components referred to the disc field and including the H I data of JvM is presented in Figs. 3 and 4.

The cone field is discontinuous and can not be plotted with the contour-plotting program mentioned. A velocity field drawn by hand, based on the measurements, is seen in Fig. 5. The positions of the slits, showing the cone velocity field, have been indicated as well as the parts of the slits where double lines have been measured.

Supernova1983V: This supernova was first discovered by R. Evans on November 25.5 UT 1983 (IAU Circ. 3895). It was independently discovered on November 27.17 UT 1983 on a CCD exposure during a demonstration of the ESO/MPG 2.2 m telescope (Lindblad & Grosbøl 1983) – a few days before the start of our 1983 observing run.

The supernova appeared in a small distinct H II region at the front of the dust lane along the Western side of the bar. The off-set coordinates are

$$x = -\Delta\alpha \cos \delta = 57''.1, \quad y = \Delta\delta = -29''.8.$$

Spectrum 22(L29:0), obtained on September 9, 1981, with the IPCS, was placed over the H II region L29 (in the immediate neighbourhood of which, incidentally, the supernova 1957C had appeared). In absence of a particular choice the spectrum was obtained with the default position angle 0° . As it happens, the slit fell, $108''$ South of L29, exactly on the H II region in which supernova 1983V appeared two years later.

In spectrum 2(n:246), obtained on November 30, 1983, the slit was by purpose placed over the supernova, and it contains a short part of the supernova spectrum. Spectrum 12(*D:353) covered the position of the supernova in November 1988.

5. Discussion

According to the analysis of JvM, the PA of the line of nodes is 220° . Spectrum 1(n:225) runs closely along the line of nodes (and crosses the H II regions L2 and L4). Spectrum 5(n:318) runs closely perpendicular to the line of nodes, and deviations from circular motion are clearly seen.

The disc velocity field pictured in Figs. 3 and 4 presents evidence of strongly non-circular motions. Particularly obvious is the twist of the iso-velocity contours in the bar region due to streaming motion along the bar and the shock-like behaviour of the gas motions at the dust lanes on the front side of the bar. The algorithm for deriving the velocity field from measurements along the slits implies some smoothing as explained above. In the original spectra, where the slit crosses the dust lane along the bar, the velocity gradient is much steeper than seen in Fig. 3. This can be seen in spectra 12(*D:353), 14(*E:309), 17(*F:323), 18(*F:355), and 24(L33:0) that cross H II regions at the edges of the dust lanes along the bar. The figure might be compared with the velocity field drawn by Lindblad & Jörsäter (1987), based on then available long slit spectra, that enhances the strong velocity gradient $8''$ SE of the nucleus. Detailed comparisons with models (Lindblad et al. 1996; Hjelm & Lindblad 1996) thus use the high spatial resolution slit data directly. The smoothed velocity fields just illustrates the global picture, and the velocity fields are an illustrative complement to the presented data. In spectrum 24(L33:0) Jörsäter (1984) also measured absorption line stellar velocities showing a much smoother behaviour across the bar.

The twist of the iso-velocity contours in the nuclear region within $20''$ from the centre was interpreted by Teuben et al. (1986) as due to the existence of an inner Lindblad resonance due to the bar, where orbits would shift from families of orbits elongated perpendicular to those elongated along the bar. This was confirmed by the simulations of Lindblad et al. (1996). Evident in Fig. 3 are wiggles in the iso-velocity contours tracing the main spiral arms, as pointed out by JvM. Also here, the optical measurements show stronger gradients when the slit crosses an absorption lane along a spiral arm, due to the higher spatial resolution along the slit, e.g. 14(*E:309) (Lindblad & Jörsäter 1987).

We believe that this data set, complemented with the H I velocity data, can serve as an excellent observational data base for comparisons with theoretical dynamical modeling of gas kinematics. The good coverage in dynamically interesting regions, i.e. the nuclear, bar and spiral arm regions, makes NGC 1365 a suitable object for hydrodynamical simulations (Lindblad et al. 1996).

The cone velocity field of high excitation gas, displayed in Fig. 5, differs drastically from the disc field. Split lines can be seen primarily where the difference between the two fields is the largest, i.e. in the SE and NW corners of the

field. These are also the regions where Phillips et al. (1983) and Edmunds et al. (1988) found double-component structure in the [O III] $\lambda 5007$ line. In the central region the two velocity fields are not separated and the cone field includes a contribution from high excitation gas following the disc velocity field. Hjelm & Lindblad (1996) modeled this field in terms of a biconal outflow of high excitation gas from the nucleus overlaying the contribution from gas in the disc, and where the counter-cone is seen partially absorbed by dust in the disc. Line ratios have no physical meaning where the two components of the velocity field cannot be separated. Spectrum 10(n:335), however, shows split emission lines of H α , [N II] and [S II], permitting line ratios to be derived for both the cone and disc components (Hjelm & Lindblad 1996).

Fig. 3. Radial velocity field of the disc component based on the present data and H I 21 cm VLA observations by Jörsäter & van Moorsel (1995). Inside $R = 50''$ the map is based entirely on optical data and outside $R = 80''$ entirely on H I data. The weights of the two sets of data change gradually in the transition region. As a result the nominal spatial resolution changes from $3''.5$ for $R < 15''$, then increases to about $20''$ at $R = 60''$ and comes down to the resolution $11''.5 \times 6''.3$ of the radio map when R reaches $80''$. The zero point of velocity is $+1630 \text{ km s}^{-1}$ and the interval between contours are 20 km s^{-1} . The straight line indicates the line of nodes

The compiled velocity field of Figs. 3 and 4 is available by anonymous ftp 130.237.166.102. The directory is pub/galaxies/papers. The data is stored in fits format in file n1365vf.fits, and information on format, pixel size, etc. is found in file n1365vf.info.

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Fig. 4. Radial velocity field of the disc component in the nuclear region. The zero point of velocity is $+1630 \text{ km s}^{-1}$ and the interval between contours are 20 km s^{-1} . The straight line indicates the line of nodes

Fig. 5. Radial velocity field for the cone component. The zero point of velocity is $+1630 \text{ km s}^{-1}$ and the interval between contours are 20 km s^{-1} . The positions of the spectrograph slits are shown as straight lines, and regions where two line components have been measured are shown as double lines

Appendix

A. Contour maps based on randomly oriented spectrograph slits

Spectral slit measurements sample a profile through the two dimensional velocity field of the galaxy. Small scale structure in the velocity field along a profile are measurable, but structure on a scale smaller than the local spacing between various profiles cannot in general be recovered from the measurements.

The individual observer can attempt to interpolate between the measurements by direct inspection using his/her personal a priori knowledge about NGC 1365 and about the dynamics of this type of galaxy. This of course is a subjective procedure and not quite satisfactory as a research tool.

In such a situation it is helpful to have an automatic map making procedure. The algorithm should be based on a few simple a priori assumptions which are well understood and generally acceptable. Consequently, it cannot take into account all available information about the particular galaxy NGC 1365, but it could offer a standardized starting point for a more detailed analysis of the velocity field.

Each measurement is allocated to the closest pixel on a square image grid $\mathbf{m}$; the unoccupied pixels are formally set to zero. A second similar grid, $\mathbf{w}$, contains the weights to be given to the individual measurements. If, for example, all measurements are to be used with the same weight, then the measured pixels in $\mathbf{w}$ are set $= 1$ and the not measured pixels are set $= 0$.

In the algorithm used here we define a set of K two dimensional continuous functions $f_k(\mathbf{r})$, $k=1,2,3,\dots,K$, where $\mathbf{r}$ is the position vector in the image plane. We find a least squares solution for a set of coefficients a_k so that the continuous function

$$g(\mathbf{r}) = \sum a_k f_k(\mathbf{r})$$

becomes a good fit to the radial velocity at the positions $\mathbf{r}_i$ where this has been measured. Choosing a regular set of Fourier components out to some maximum spatial frequency $|\rho|_{\max}$ for the functions f_k has important advantages:

First, any velocity distribution can be described by $g(\mathbf{r})$ to within a known spatial resolution determined by the value of $|\rho|_{\max}$. No algorithm can discover details not present in the measurements and $|\rho|_{\max}$ must be chosen in a conservative way. The corresponding maximum resolution should be related to the typical spacing between the measurements (or spectrograph slits).

Second, the coefficients in the least squares equations can be calculated in a simple way. The general matrix and vector elements can be written:

$$\begin{aligned} \sum \mathbf{w}(\mathbf{r}_i) f_p(\mathbf{r}_i) f_q(\mathbf{r}_i) &= \text{Re} \mathbf{W}(\rho_p - \rho_q) + \\ \text{Im} \mathbf{W}(\rho_p + \rho_q) \\ \sum \mathbf{w}(\mathbf{r}_i) \mathbf{m}(\mathbf{r}_i) f_p(\mathbf{r}_i) &= (1/\sqrt{2}) \{ \text{Re} \mathbf{M}(\rho_p) + \\ \text{Im} \mathbf{M}(\rho_p) \} \end{aligned}$$

the sums to be taken over the whole image grid. Here $\mathbf{W}(\rho)$ is the Fourier transform of $\mathbf{w}$, and $\mathbf{M}(\rho)$ the Fourier transform of $(\mathbf{w} \cdot \mathbf{m})$. ρ_p is the spatial frequency corresponding to the function $f_p(\mathbf{r})$. Thus, the often many thousand elements can be read directly from the transforms of $\mathbf{w}$ and $(\mathbf{w} \cdot \mathbf{m})$.

Third, we can bias individual spatial frequency components in the least squares solution: an increasingly strong bias against higher spatial frequency components – and thus towards a smooth solution – has the desirable consequence that the algorithm does not invent fine structure where such is not warranted by the measurements. The method used here is to add suitable bias terms to the diagonal elements in the least squares matrix.

Sometimes, as in this case, the central portions of the field are better covered by measurements than further out. It is possible to produce a solution, in which the formal spatial resolution decreases with the distance from the centre. Express the location of the measurements in log-polar coordinates:

$$\begin{aligned} \xi &= \ln(r) \\ \eta &= \arctan(y/x) \quad (x^2 + y^2 = r^2) \end{aligned}$$

Apply the least squares solution in the (ξ, η) domain and make a coordinate transform back to the normal Cartesian grid. Both methods have been used in calculating the maps of Figs. 3 and 4.

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