METHODICAL IMPROVEMENTS OF MAGNETOGRAPHIC MEASUREMENTS

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Abstract: In order to obtain correct magnetic field strengths for both weak and strong magnetic fields by magnetographic measurements and to avoid the well-known difficulty of calibration, the following improvements are made:

1. Selection of a Zeeman triplet line (Fe I λ 5253.5 Å) which (a) is little temperature sensitive, (b) is little distorted by blends, (c) has only a moderate splitting in order to avoid ambiguity of the signals for large field strengths.
2. Calculations of theoretical calibration curves taking into account (a) realistic model atmosphere, e.g., an umbral model for $H \geqslant 1000$ G, (b) the correct size of input and output apertures and the instrumental profile of the spectrograph.
3. Application of stray-light correction (scattering and blurring).
4. Magnetographic maps of several large sunspots and their surroundings are compared with maps from photographic observations (circular analyser, line Fe I λ 6302.5 Å) of the same regions.

In the spot centre, agreement is obtained between the maximum longitudinal field strength from the magnetograph and the field strength determined photographically without artificial manipulation of the calibration curves. Reasonable values for the continuum intensity are derived simultaneously.

Transverse magnetic fields seem to be too large, which is probably caused by instrumental polarization. Efforts are being made to solve this problem.

Introduction

For the understanding of the physics of solar active regions, investigation of the magnetic fields is one of the main problems. Our interest is not only directed to strong fields in sunspots which are at present being measured most reliable by photographic or visual methods, but also to the distribution of the weaker fields outside the sunspots, which is very important. The latter are successfully observed with magnetographs for many years.

So far considerable difficulties are being encountered in measuring the magnetic field components in sunspots with magnetographs, particularly due to the lack of correct calibration curves. Comparing magnetograph measurements with photographic and visual Zeeman measurements, on the one hand, and with results obtained by means of a laboratory magnet, on the other hand, Severny (1967) found large discrepancies between theoretical and empirical calibration curves. For these reasons we checked once more some of the theoretical and empirical foundations of magnetograph observations and we want to report here on some possible methodical improvements in observing the distribution of strong fields.

Starting in the summer of 1972 at the Einsteinturm Observatory, solar magnetic fields are being measured employing an Irkutsk-type vector magnetograph. It was manufactured in the U.S.S.R., on the basis of a SibIZMIRAN design, and has been described by Kuznetsov, Kulin and Stepanov (1966). The magnetograph records three signals for the magnetic field components, one for the line-of-sight velocity and also two for the intensities of the continuum and line core.

The Magnetographic Method

The magnetographic method is based on the determination of the polarization properties of the spectral lines by transforming the polarization differences into intensity differences, which then can be measured, by means of an analyser. Most magnetographs receive light passing through two or three output apertures, the position and the widths of which are shown in Figure 1, relative to the photospheric and spot profiles of a magnetic sensitive line. One of the most important foundations to obtain correct results by magnetograph measurements is the careful selection of the spectral line used. Some important aspects, which generally have to be respected in investigating magnetic fields in sunspots, were discussed by von Klüber (1948).

Among them the temperature sensitivity of the line is much more important for the magnetographic method than for the photographic one. The temperature difference between the photosphere and spot can strengthen the line in the spot until saturation occurs, which corresponds to a very flat part on the calibration curve, where exact measurements are impossible.

For simultaneous measurements of strong and weak magnetic fields it is useful to choose lines with moderate splitting, because otherwise in one case by shifting the sigma components outside the slits one gets a reversion of the calibration curve (and thereby two or possibly even three solutions) and in the other case it is impossible to determine weak field strengths exactly. Figure 2 shows theoretical calibration curves for two photospheric models and a spot model. One can see that the calibration curves for the line Fe I 5250.2 Å exhibits this reversal for both the spot and the photospheric models, while this is not the case for the line Fe I 5253.5 Å. All measurements in spots, made in the line 5250.2 Å, which do not take into account its temperature sensitivity may contain large errors.

On contrary the line 5253.5 Å accomplishes the demands for temperature insensitivity and moderate splitting. The line is also free from blends and is situated within the maximum sensitivity of the photomultipliers. Thus we chose this line for our magnetograph measurements.

For calculating the calibration curves, by means of which the measured signals are transformed into magnetic field intensities, photospheric models have often been used for any field intensity in the past. Although the 5253.5 Å line is not very temperature sensitive, in order to increase the accuracy of the magnetograph measurements, true spot models are recquired for stronger fields. Considering our own spectro-photometric investigations of some well-known triplets and some non-split lines in the photosphere and spots, and the comparison with various model calculations, we decided for the models by Holweger (1967) and Stellmach and Wiehr (1970). For field intensities of less than 1000 Gauss the Holweger model and for field intensities of more than 1000 Gauss the Stellmach-Wiehr

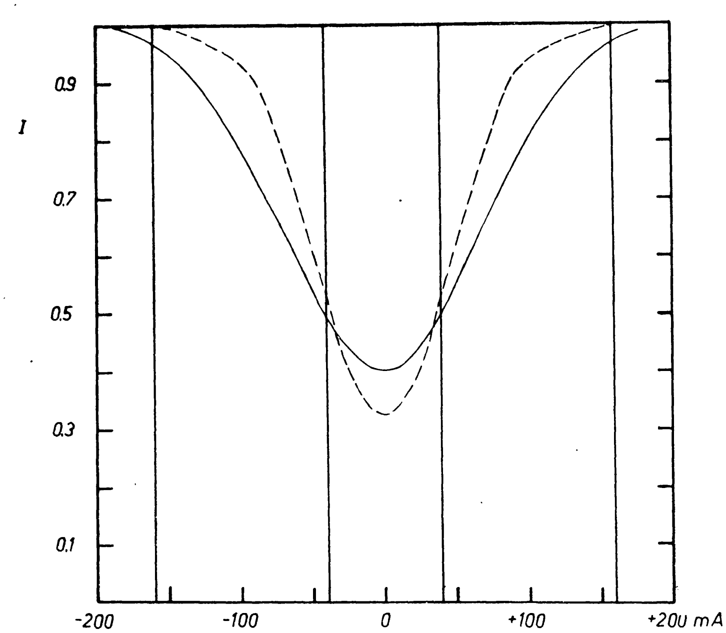

Fig. 1. Profiles of Fe I λ 5253.5 Å on the photosphere (dashed line) and spot (solid line) with positions and widths of the output aperture of the spectrograph observed with a 92 m Å input aperture.

model is used. These two parts of the calibration curve pass over into one another without a jump.

In calculating the calibration curves practically, it is necessary to consider the real widths of the input and output apertures. In order to fix them, we drew on the investigations of the dependence of the signal-to-noise ratio on the widths of the slits by Deubner (1962) and chose the width of the input aperture equal to half the width of the photospheric line. Of course in calculating the calibration curves

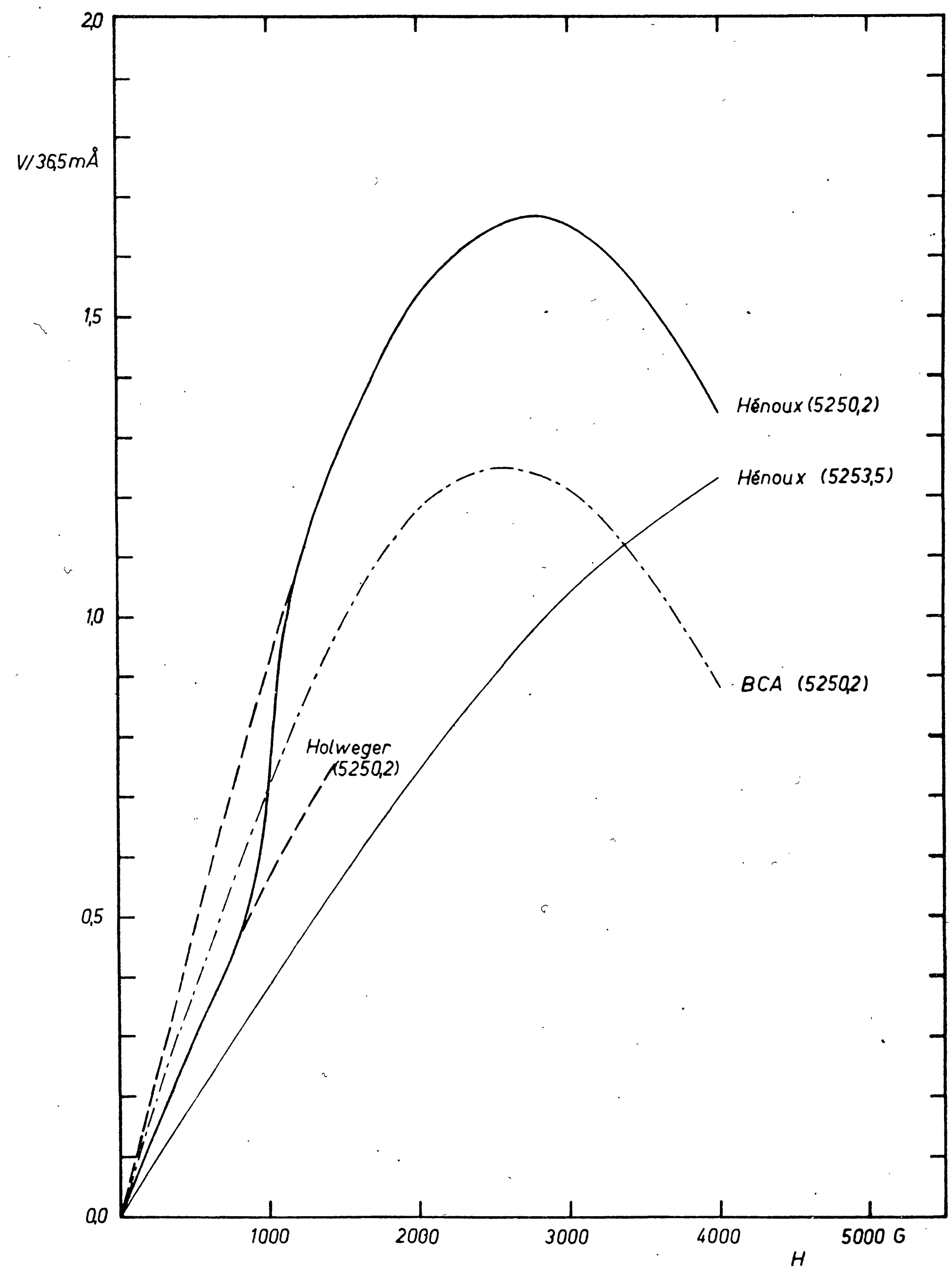

Fig. 2. Magnetographic calibration curves for the Fe I lines λ 5250·2 and 5253·5 Å showing the influence of different models and different lines.

it is necessary to start with the line profiles which are composites of the width of the input aperture and have to be integrated over the width of the output aperture (Fig. 1).

In order to obtain the relation between the theoretically calculated calibration curve and the measured values, one must derive the calibration constants for the magnetograph response in the magnetic field channels. A suitable method using the Doppler shift of the spectral lines at the solar limb was described by Aleksandrovich, Kuznetsov and Stepanov (1967). In principle we adopted the same method, the only difference being that we generated an artificial Doppler shiftly tilting the glass plate of the Doppler compensator (more details on calibration, scanning and evaluation in a forthcoming paper in Supplement Series of Solar Data (HHI)).

In discussing the results, we want to exclude the transverse field for the time being. The results in question are given in the form of tables, the columns of which correspond to the individual traces in the scanning. The distance of the points within the grid was chosen to render the scales in the two coordinate directions equal. The maps with the continuum intensity clearly show the large spots, as well as their shape. But spots which are only a little larger than the distance of the two traces (7.5 sec of arc) are only seen as existing. On maps of the line-core intensity the faculae are seen distinctly. Many sunspots which are no longer discernable on the intensity maps, however, are still visible in the maps of the longitudinal field. Of course, their field-strength values are much smaller than the true values. However, in still has to be shown that the reason for this is not just the relatively large input aperture of 2.5×6 sec of arc.

The maps with the line-of-sight velocity show the maximum velocity within the penumbra of the large spots. The variation of velocity in such spots amounts to 1 km/sec. Within regularly shaped spots the amount and the distribution of the line-of-sight velocity corresponds approximately to the expected Evershed effect. Within the entire area the variation of the velocity amounts to 2 km/sec.

The Photographic Method

Magnetograph measurements of three large sunspots were made for comparison with measurements of the Zeeman splitting in spectrograms of the same spots. This comparison is offered for different reasons. Firstly, the Einsteinturm Observatory has many years experience with the photographic method and its results have been well established. Secondly, the photographic method offers some advantages of a practical nature which the magnetographic method has not got. Thus the photographic method can operate with a narrow spectrograph aperture and, therefore, besides the distortion by seeing practically no other distortions, also not by the entrance aperture, must be considered. Moreover, the method is also considerably less sensitive to stray light and instrumental polarization than the magnetographic method.

The photographic method uses spectrograms of the Fe I line λ 6302.5 Å exposed through a homogeneous quarter-wave plate and Rochon prism. The height of the spectrograph aperture is determined by the prism splitting the beam, the dimension of which is 0.9×103 sec of arc. The linear dispersion amounts to 1.5 mm/Å.

The spectrograms are obtained by expositions, which correspond to equidistant (distance 7.5 sec of arc) intersections across the main spot of a group. The line splitting is measured along the aperture direction at the same distance (7.5 sec of arc) and the magnetic field strength determined. The splitting is measured by means of a spectro-comparator, whereby the spot spectrogram is compared with a spectrogram of the undisturbed disk centre (Grotrian, 1953; Grotrian et al., 1955).

For comparison with the magnetographic results, the photographic results are also represented in the form of maps, where the first gives the field intensity and the polarity for every point of a square grid with intervals of 7.5 sec of arc, the second an isogauss representation and the third a drawing of the distribution and the shape of the spots. Although every intersection is represented only by one exposition the mean error of the field-intensity values is only ± 85 Gauss.

Comparison of the Results of the Magnetographic and Photographic Methods

Maps with the magnetic field of three large spots (diameter of the umbra larger than 15 sec of arc), which were observed near the centre of the disk on June 5 and 6 and on July 6, 1972, are compared. The spots investigated were the main spots of G- and I-groups according to the Zürich classification. Their maximum field intensities determined

Table 1. Effect of different stray-light corrections on the longitudinal-field strength in sunspots

−10	−10	−53	−62	−25	−125	−62	−41	−54
−14	−7	−30	−158	−52	−233	−110	−81	−37
−8	15	19	−200	−182	−303	−191	−139	−28
−9	23	47	−221	−302	−260	−360	−193	−30
−12	22	8	−467	−352	−403	−502	−168	−31
−8	29	−128	−743	−396	−853	−547	−120	−25
−3	31	−147	−497	−532	−1022	−447	−30	−35
0	26	−80	−300	−618	−530	−335	−9	−36
2	21	−59	−163	−438	−220	−213	−2	−14
0	17	−46	−86	−290	−61	−84	−2	−7
10	8	−34	−55	−156	9	−46	−2	−2
15	8	−8	−13	−56	7	−38	0	2
15	39	6	0	−15	6	−34	6	3
18	78	11	2	−5	2	−23	8	3

Without correction

−12	−8	−66	−52	−17	−121	−48	−35	−55
−17	−10	−35	−179	−29	−252	−103	−77	−35
−7	19	29	−213	−193	−332	−178	−143	−24
−9	26	69	−201	−330	−226	−379	−212	−28
−14	22	31	−536	−365	−379	−540	−173	−31
−9	33	−155	−985	−363	−1024	−592	−125	−21
−4	37	−168	−538	−533	−1327	−462	−8	−37
0	29	−71	−304	−707	−567	−349	0	−42
2	23	−56	−152	−462	−207	−226	3	−12
−3	19	−47	−75	−303	−42	−70	0	−6
11	6	−38	−56	−159	29	−40	−2	−2
16	0	−6	−6	−47	10	−39	0	3
14	38	7	4	−9	8	−37	7	3
16	80	11	2	−3	2	−24	9	3

Only restoration with $\psi = 0.5\ G_2 + 0.5\ G_7$

−11	−8	−63	−53	−20	−120	−52	−34	−54
−16	−9	−34	−173	−35	−245	−106	−78	−36
−7	18	25	−208	−192	−324	−180	−141	−26
−9	25	62	−201	−324	−234	−373	−207	−29
−13	21	24	−504	−364	−385	−526	−172	−32
−8	30	−150	−900	−377	−956	−577	−126	−22
−3	34	−163	−523	−530	−1227	−455	−16	−36
0	27	−73	−302	−681	−554	−343	−5	−40
3	22	−57	−155	−452	−211	−221	0	−12
−2	18	−47	−79	−296	−49	−72	0	−6
11	6	−37	−57	−156	23	−41	−2	−2
16	2	−6	−8	−48	8	−38	0	3
15	37	7	3	−10	6	−36	7	3
17	78	11	2	−4	2	−23	9	3

Only restoration with $\psi = 0.8\ G_2 + 0.2\ G_7$

−14	−9	−75	−60	−19	−139	−55	−39	−62
−19	−11	−39	−211	−33	−295	−118	−88	−40
−8	21	33	−255	−227	−395	−207	−163	−27
−10	30	82	−267	−413	−289	−449	−243	−31
−15	25	36	−994	−663	−614	−653	−201	−35
−10	38	−187	−2010	−892	−2656	−724	−146	−24
−4	43	−201	−722	−1717	−2697	−561	−10	−41
0	33	−48	−369	−1022	−754	−418	0	−48
2	26	−66	−182	−567	−253	−267	4	−13
−4	22	−55	−89	−363	−50	−81	0	−7
13	7	−43	−66	−188	34	−46	−2	−2
18	0	−7	−7	−55	12	−44	0	3
16	43	7	5	−10	9	−42	8	3
18	91	12	3	−4	2	−27	10	3

Restoration with $\psi = 0.5\ G_2 + 0.5\ G_7$ and correction for scattered light (12 %)

by photographic Zeeman measurements are about 2700 Gauss, however, according to our magnetograph measurements, they are only about 1000 Gauss. It will be shown that this difference depends on stray light.

By investigating the spot spectra we found between 8 and 10 per cent scattered light under moderate observing conditions at the disk centre, the notations used being the same as Zwaan's (1965). Table 1 shows the influence of the stray-light correction. One can see that the distortion of the distribution in the sun of two Gaussians G_2 and G_7 (with sigma 2.5 and 7 sec of arc respectively), which represents the visible part, is of minor importance for the maximum field intensity within large sunspots. Table 2 shows the results of photographic and magnetographic methods derivated from the same spot (the scale is identical for the two methods, distance of the columns 7.5 sec of arc, distance of the lines 3.75 sec of arc). Only after introducing the stray-light correction a detailed comparison of the different maps from the magnetograph and those from the photographic method becomes meaningful. Here we want to report briefly on the most important results of this comparison.

Because of the uncertainty in fixing the intensity of the undisturbed photosphere, qualitative agreement between maps of the continuum and the line-core intensity exists only within large sunspots. Inside the umbra of the main spots the photospheric method yields intensities higher than 1000 Gauss, the magnetographic method, however, at the boundary of the umbra only longitudinal field intensities of 200 Gauss. Similar relations are found in the penumbra, where the photographic method yields 300 to 1000 Gauss, the magnetographic, however, only 20 to 200 Gauss (Table 2). In small spots Zeeman measurements give 500 to 800 Gauss, the maps from the magnetographs for these cases show only 100 to 200 Gauss. Such discrepancies can partly be explained by the fact that Zeeman measurements for strong fields yield these field intensities, but we compared these results with the longitudinal field intensity from the magnetograph. Moreover, the distortion with the

Table 2. Distribution of field strength inside the sunspot
N 09 E 23 of July 6, 1972

From photographic observations									From magnetographic observations								
		801	460	452	525	380	608	380	19	11	39	211	33	295	118	88	40
		1271	1014	1246	1194	971	931	498	8	21	33	255	227	395	207	163	27
438	539	1740	1568	2040	1862	1561	1254	616	10	30	82	267	413	289	449	243	31
462	917	1906	2146	2372	2233	1991	1592	779	15	25	36	994	663	614	653	201	35
486	1294	2072	2724	2704	2604	2420	1930	942	10	38	187	2010	892	2656	724	146	24
438	1136	1766	2391	2521	2450	2248	1694	727	4	43	201	722	1717	2697	561	10	41
390	978	1460	2058	2338	2296	2076	1457	511	0	33	84	369	1022	754	418	0	48
	790	1155	1609	1829	1861	1330	1057		2	26	66	182	567	253	267	4	13
	601	849	1160	1319	1426	584	656		4	22	55	89	363	50	81	0	7
				953	1000				13	7	43	66	188	34	46	2	2
				587	573				18	0	7	7	55	12	44	0	3

Table 3. Distribution of inclination angle (left part) and transverse-field strength inside the sunspot
N 09 E 23 of July 6, 1972

0	0	−63	−77	0	−51	−71	0	−66	0	0	−135	−248	0	−172	−147	0	−128
0	0	−77	−62	−79	−41	−51	−63	−73	0	0	−156	−388	−160	−255	−145	−160	−123
0	81	74	−55	−48	−43	−57	−56	0	0	132	113	−365	−249	−366	−318	−243	0
0	82	74	−31	−38	−63	−43	−49	0	0	219	277	−161	−323	−570	−414	−276	0
0	86	84	−42	−47	−55	−40	−56	0	0	333	359	−897	−712	−897	−548	−295	0
0	84	−64	−57	−53	−50	−38	−60	0	0	378	−380	−3037	−1195	−3260	−562	−255	0
0	83	−70	−60	−55	−41	−31	−87	0	0	358	−561	−1283	−2468	−2402	−336	−197	0
0	83	−83	−66	−41	−25	−31	90	0	0	257	−666	−825	−891	−353	−251	179	0
0	80	−84	−73	−43	−50	−41	0	0	0	140	−615	−599	−524	−300	−233	0	0
0	0	−82	−76	−42	−78	−61	0	0	0	0	−412	−363	−329	−238	−137	0	0
0	0	−82	−76	−55	79	0	0	0	0	0	−308	−252	−269	164	0	0	0
0	0	−88	−88	−76	0	0	0	0	0	0	−204	−161	−206	0	0	0	0
0	0	86	0	−86	0	0	0	0	0	0	114	0	−138	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

relatively large input aperture has another cause. In the case of the penumbra the stray light from the nearby photosphere also plays a certain role.

The Problem of the Transverse Field

The maps with transverse field intensity, dip angle and azimuth angle show only three values different from zero, where the transverse field intensity exceeds a certain threshold value. We have determined this threshold to be about a hundred times larger than for the longitudinal field intensity exceeds a certain threshold value. We have determined this threshold to be about a hundred times larger than for the longitudinal field, because theory and practice for the case of weak transverse fields give such a relation between the signals. On most maps the field intensity within bright faculae exceeds the threshold value. Thereby transverse field of 300 Gauss and more are sure. Within the umbra of large spots the transverse field strength exceeds 2000 to 3000 Gauss, in single cases it even attains 4000 Gauss. Table 3 shows the dip angle and the transverse-field intensity for the same spot as above.

The dip angles by these circumstances are of course influenced. They amount to about 90 degrees, where it is expected that preferably longitudinal fields exist within faculae. Also in the centres of large spots near the disk centre angles between 20 and 60 degrees are observed. It is possible that herein partly the influence of the instrumental polarization is expressed.

The reflexions of the sunlight on the mirrors of the coelostat and telescope, as is well known, change the polarization condition of light. The influence of this instrumental polarization on magnetograph measurements was investigated by Jäger (1972). It is shown that some non-diagonal elements of the instrumental matrix become relatively large, i.e. the instrumental polarization caused by them could possibly be responsible for the errors in measuring transverse fields. In any case, it would be possible to show by an example that the instrumental polarization gives large errors of the dip angle and therefore, also of the transverse field. Further it has been proved that one must firstly take care to eliminate those instrumental influences which results in a miscentering of the line, because otherwise all magnetic-field signals and also the line-of-sight velocity are measured incorrectly. The miscentering can be corrected by a retardation plate with a given retardation. The position angle of the plate depends on the adjustment of the coelostat and the reflexion properties of the mirrors and has to be calculated in advance. Only after this kind of compensation the use of a glass plate to compensate the second part of the intrumental polarization will be useful. However, for the measurements in question we have only employed the glass-plate compensation, thus in all parameters determining the magnetic vector there could be certain errors. We have no experience as to their magnitude; we can only refer the reader to the results of Jäger.

Methodical Improvements in Design

In this report we intended to show that the most important causes of the discrepancies between the photographically and the magnetographically obtained magnetic field intensities within sunspots can be found, and also some methods to eliminate these discrepancies. It is clear that the method used can be improved further. Thus the problem of the correct selection of the line could perhaps be solved more favourably, if it were possible to find a line in the red part of the spectrum, which satisfies the necessary conditions. In this way one could simultaneously solve the stray-light problem more favourably, because there the intensity ratio between spot and stray light increases, i. e. the stray light looses its influence partly. Moreover, we have already improved the methods of stray-light determination by measuring the intensity distribution inside and outside the limb before and after the scanning of an active region. Thereby an independent method for stray-light determination is obtained.

After we have eliminated the largest errors in the magnetograph measurements in the form of the stray-light correction, the errors caused by instrumental polarization and too large an input aperture still remain. As regards the instrumental polarization Jäger shows two ways of taking this into account. We shall use one of them in the next period of observation. We hope to be able to eliminate with it the cause which, in particular, distorts the transverse fields. Finally the technical problem of the distortion by the input aperture remains. Here, we shall also make progress by modernizing the scanning technique, which should permit us to reduce the input aperture and distance of two scans by half.

These improvements should help us to obtain not only qualitative distributions of the spot magnetic field, but also quantitative distributions, including the complete vector, and in this way to provide for understanding the physics of solar active regions.

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