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DOT STRATEGIES VERSUS ORBITER STRATEGIES

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ABSTRACT

The Dutch Open Telescope is a high-resolution solar imager coming on-line at La Palma. The definition of the DOT science niche, strategies, and requirements resemble Solar Orbiter considerations and deliberations. I discuss the latter in the light of the former, and claim that multi-line observation emphasizing hydrogen diagnostics represents a key strategy.

Keywords: solar telescopes, solar magnetism, solar atmosphere, solar spectroscopy.

1. DUTCH OPEN TELESCOPE

The Dutch Open Telescope (DOT) at the Roque de los Muchachos Observatory on La Palma is a novel and innovative optical solar telescope which images the solar atmosphere at $0.2''$ resolution during extended durations through combining an open wind-flushed structure (Figure 1) with excellent optics and large-volume speckle reconstruction. The telescope was proposed by C. Zwaan in JOSO–LEST context in the 1970's, was designed and built by R.H. Hammerschlag during the decades since, and has recently been turned into a speckle imager by P. Sütterlin. Details are given in Rutten *et al.* (2001a, 2001b)[1].

The DOT is presently being equipped with a five-camera speckle imaging system described by Sütterlin et al. (2001). It will enable synchronized speckle burst recording simultaneously of the deep photosphere, the low chromosphere and the high chromosphere using the first three diagnostics listed in Table 1. The fourth camera will acquire high-resolution Dopplergrams and possibly Stokes vector magnetograms using Ba II 4554 Å. The fifth camera will provide broad-band near-Hα continuum images to enable tuned narrow-band Hα speckle restoration using the two-channel technique of Keller & von der Lühe (1992).

Figure 2 shows a sample G-band image from the first camera. It illustrates the high resolution achieved with the DOT and it also illustrates the important advantage that speckle processing has over adaptive optics: the *whole* field as delimited by the camera chip is restored to the $0.2''$ diffraction limit (through splitting the full image into hundreds of isoplanatic patches that are treated independently). This quality is reached whenever the La Palma seeing is moderately good, *i.e.,* Fried parameter $r_0 \approx 10$ cm.

2. DOT STRATEGIES

[1]Preprints available at http://dot.astro.uu.nl.

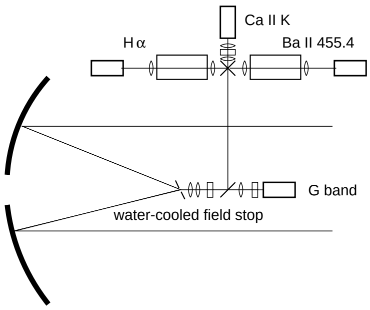
2.1 DOT science

The science niche that the DOT may fill the coming years[2] consists of delivering long-duration image sequences that excel in angular resolution ($0.2''$ consistently), field size ($92\times73''$ with the present 1296×1030 px cameras), multi-height sampling (deep photosphere, low and high chromosphere), and diagnostic value (line profile sampling of Hα and Ba II 4554). These properties make the DOT a tomographic mapper of the time-dependent magnetic topology of the solar atmosphere at intrinsically different heights, useful and desirable to all issues in which magnetic topology plays a role — ranging in spatial scale from tiny network flux tubes to extended active regions, in temporal scale from high-frequency oscillations to active-region evolution, in dynamical behavior from stable (but oscillating) sunspots to flares, erupting prominences, and coronal mass ejections, in pattern topology from ephemeral field emergence and network field dispersal to the structure and evolution of active regions and the anchor constraints to filaments/prominences and flare build-up.

A key topic for high-resolution topology mapping is the nature of the magnetic coupling between the high-beta and low-beta parts of the solar atmosphere. It is easy to claim paradigmatically that photospheric flux tubes expand into magnetic canopies and combine into coronal loops, but this picture is far too schematic. The actual “canopy” (which should be *defined* as the $\beta = 1$ manifold) and the actual “transition region” (which should be *defined* as the 50% hydrogen ionization manifold) are highly folded, finely structured, and highly dynamic surfaces, not obeying “layer”or “shell” geometry at all. Mapping actual canopy and transition region topologies and dynamics is an essential step towards understanding the magnetic coupling between the $\beta > 1$ solar interior and photosphere, the $\beta < 1$ upper chromosphere and low corona, and the outer corona and wind.

2.2 DOT wavelength selection

[2]The DOT future is uncertain since its present funding runs out by the spring of 2002. Continuation hinges not only on funding but also on a fundamental Utrecht University policy decision to continue or discontinue solar physics. It should be noted that the rich solar physics tradition at Utrecht (including Minnaert, de Jager, Zwaan, and many other well-known scientists) is largely past glory, with only two tenured staff members (myself and Hammerschlag) presently devoted to solar physics. This paper assumes that our DOT efforts will continue.



diagnostic	λ	$\Delta\lambda$	domain
G band	4305 Å	10 Å	low photosphere
Ca II H	3968 Å	1 Å	low chromosphere
Hα	6563 Å	0.25 Å	high chromosphere
Ba II	4554 Å	0.08 Å	low photosphere

Table 1: DOT diagnostics. The G band contains many dark CH lines which vanish through CH dissociation in magnetic elements, making this band the best diagnostic to map "flux tubes" in the deep photosphere. The Ca II H line shows the magnetic field distribution higher up where the magnetic elements combine into larger network patches but the field has not yet spread all over. The field spreading into finely textured and highly dynamic magnetic "canopies" is seen in Hα, for which the DOT is equipped with the tunable Zeiss Lyot filter formerly used at the Ottawa River Solar Observatory by V. Gaizauskas. The Ba II resonance line has enhanced Doppler sensitivity to nonthermal motions at high angular resolution due to the large barium atomic mass and may also be a good Stokes line. The very narrow tunable Ba II Lyot filter used at the DOT was built by V. Skomorovsky at Irkutsk. The optics sketch at left is schematic; the actual configuration provides telecentric placement of all filters, maintains diffraction-limited resolution at all wavelengths, and has a fifth camera in near-Hα continuum for two-channel Hα restoration.

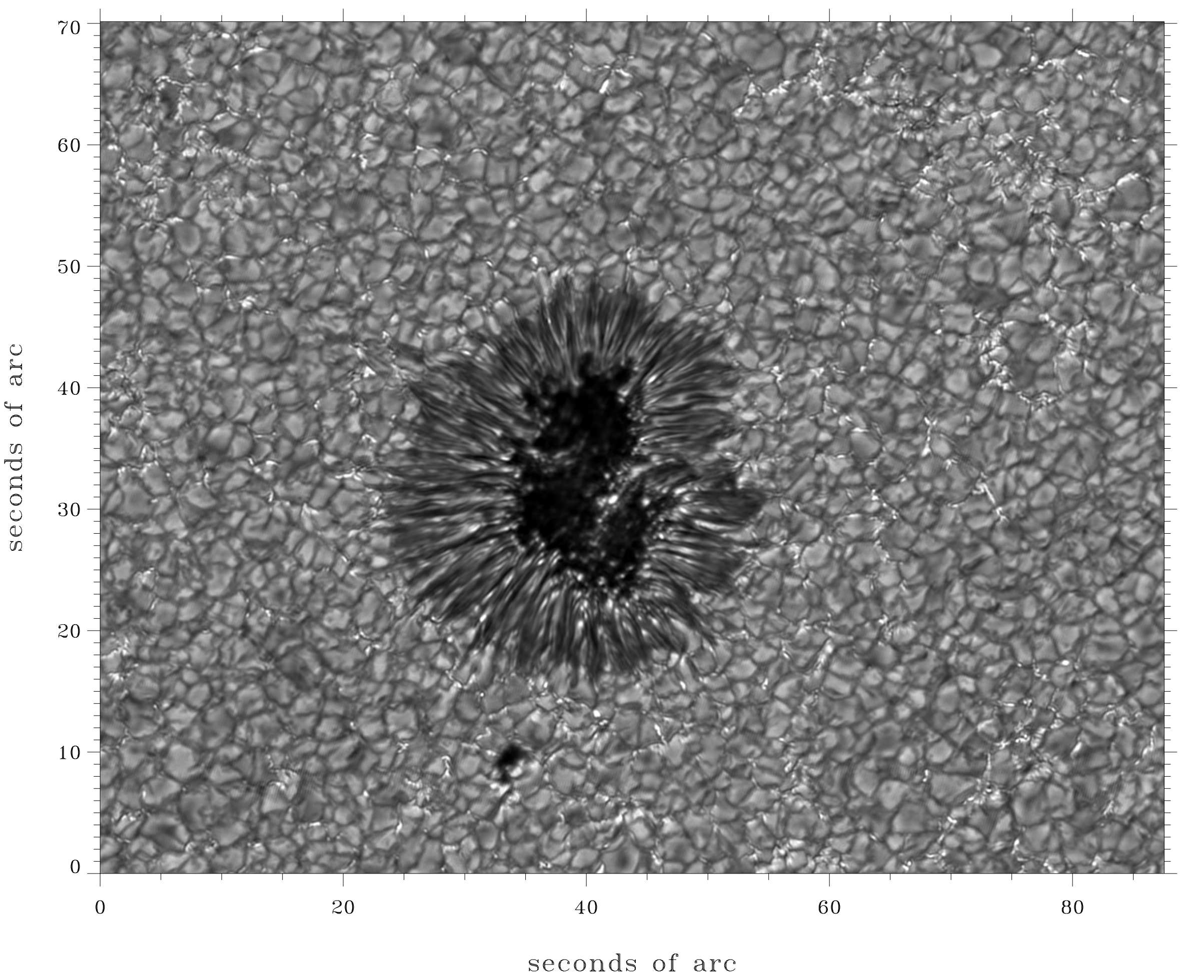


Figure 2: G-band image of sunspot AR 9407 taken with the DOT on April 1, 2001 by P. Sütterlin using the first camera of the multi-channel imaging system. The full one-hour movie sequence is available at http://dot.astro.uu.nl.

Figure 1: The Dutch Open Telescope on La Palma. The telescope and the 15 m high support tower are open to the trade wind from the North (to the right) which brings the best seeing to La Palma. When it blows sufficiently strong it confines the solar-heated boundary layer of turbulent convection to heights below the telescope and flushes the telescope itself. The parallactic telescope mount is extraordinarily stiff to avoid image shake from wind buffeting. A clamshell foldaway dome protects the telescope from (sometimes very) inclement weather. The telescope consists of a 45 cm parabolic primary (seen in the middle of the photograph) with 200 cm focal length. The primary image is mostly reflected away with a water-cooled mirror (the water storage tank is in the foreground). A small hole (1.6 mm) transmits the field of view. The slender on-axis pipe at the top of the telescope contains the focusing mechanism, re-imaging optics, the G-band filter and the G-band camera. The other four cameras of the multi-channel imaging system will be mounted at the telescope top besides the incoming beam. The speckle frames are transported by optical fibers (in the pipe) to a large-capacity data acquisition system in the Swedish solar telescope building from which the DOT is operated. Picture taken by Aswin Jägers.

I claim that Hα provides the principal diagnostic to map the actual canopy structure as missing link to fill the reality gap between the modeler's "tubes" and "loops". Quantitative interpretation of Hα filtergrams is notoriously difficult because the line mixes Dopplershifts with brightness modulation and is awkwardly sensitive to NLTE population mechanisms mixing both density and temperature variations (because its lower level is so very detached from the hydrogen ground state); in addition, it shows both optically thick and optically thin structures. These complex mixtures give high-resolution Hα movies their dramatic appearance and rich information content but also make them very hard to interpret. The Hα images and movies taken with Kiepenheuer's Domeless Refractor on Capri and by Zirin at Big Bear have contributed to the bad name of "solar dermatology" by their rich but ill-understood morphology. It takes extensive numerical line formation modeling and sufficient filtergram spacings across the line to translate Hα images reliably into quantitative maps of the actual chromospheric topology, techniques that may and must be developed now that image restoration permits profile-per-pixel extraction. Thus, I regard Zirin's love of Hα as most appropriate but Hα too harsh a mistress to tackle without precise profile determination and sophisticated profile modeling, and consider quantitative Hα mapping to be a major DOT quest.

2.3 DOT co-registration

Employing Hα as principal canopy diagnostic does not deliver insight in photosphere–corona magnetic coupling without exact co-registration with photospheric mapping (G band, Doppler, Stokes) and coronal mapping (EUV, in particular 171 Å loops and moss). The DOT is an exceedingly stiff telescope in which the five cameras will be mounted with exceptional mechanical stability, enabling permanent high-precision field alignment. Also, all frames in each speckle burst are taken synchronously at all wavelengths, ensuring exact simultaneity. The DOT Ca II images provide exact co-registration with TRACE UV images (1600, 1700 Å passbands) because the respective solar scenes correspond closely (Rutten et al. 1999). Thus, the DOT furnishes exact internal co-registration between photosphere and Hα while the close Ca II–UV correspondence provides precise Hα co-registration with TRACE's 171 Å and other EUV diagnostics.

3. SOLAR ORBITER STRATEGIES

3.1 Solar Orbiter science

It is obvious that the high-resolution EUV imaging and supportive high-resolution optical diagnostics of SO make the nature of the magnetic coupling between photosphere and corona a prime SO science topic. Even a decade from now there should be much left to do, but it is likely that the emphasis will have shifted from scenario thinking to detailed numerical modeling, surely in forward manner and perhaps through data inversion. The topics list will be the same as the DOT agenda above, with additional SO angles (literally, *i.e.,* higher latitude and co-rotating), but the content will be more quantitative than solar magnetic-coupling research is now. The instrument designs must therefore emphasize quantitative applicability.

3.2 Solar Orbiter wavelength selection

It is also obvious that most solar physicists presently studying the solar atmosphere using spectral line diagnostics are either optically thick or optically thin. The EUV imagers prefer to use DEM analysis of lines that may be assigned to optically thin structures with "formation temperature" as major line characteristic. The visible spectroscopists prefer to use lines that do not suffer from NLTE formation or partially coherent scattering, assigning "formation height" as major line characteristic. The coming years these fields of expertise must mingle. It seems highly unlikely that one may get away with not using *all* diagnostics that the solar atmosphere offers to unravel its secrets. In particular, the information content of optically thick UV lines must be appreciated as complementary to the information content of optically thin EUV lines. The photosphere–corona gap must be bridged not only through spread in formation temperature sampling but also by spread in thick–thin formation sampling.

The DOT niche and strategy summarized above emphasize quantitative Hα mapping. The principal hydrogen line, Ly α, seems similarly important and nasty. I cannot imagine that the transition region will open up all its secrets if the primary line in the whole spectrum is not exploited, and similarly so for the Lyman continuum. At the recent "Beyond Solar-B" NASA planning workshop at Huntsville, Han Uitenbroek advocated that combination of Hα and Ly α spectrometry is required to interpret either line, suggesting even that quantitative Hα mapping actually requires concurrent Ly α spectrometry and PRD modeling. This may have to wait for a next-generation "Beyond Solar-B" space observatory larger and closer than a small faraway solar orbiter, but I do think it behooves SO instrument builders to consider UV and EUV H I Lyman diagnostics.

3.3 Solar Orbiter co-registration

Quantitative tomographic mapping needs a holistic approach which not only combines hot and cool and thin and thick diagnostics but also combines imaging with spectrometry. In broad terms solar physics has advanced mostly the past decades through imaging, both from the ground and from space — it is most fitting that Alan Title receives the Hale Prize. The emphasis on spectrometry through which solar physics originally initiated astrophysics shifted to imaging (and to multi-dimensional numerical simulation) because the sun poses physics problems that are intrinsically four-dimensional in space and time and are inadequately sampled by linear spectrometer slits. The need for quantitative mapping will shift some emphasis back to spectrometry but only when done in concert with imaging. On the ground this will particularly be the case for Stokes spectropolarimetry using adaptive optics. In space, combination of imaging and diagnostic spectrometry represents the key strategy of Solar-B and similarly warrants the SO combination of EUV imaging and visible spectrometry. The combination will *only* work out if strict co-registration between the two is achieved to well below the pixel size. The DOT ensures photosphere–corona co-registration by adding Ca II imaging as link to TRACE UV imaging. The Solar Orbiter will be out in the boondocks all by its little self and *must* provide precise internal co-registration between all its wavelengths.

4. CONCLUSION

The data rate from the DOT is effectively 4 Mbit/s *after* speckle reconstruction, a hundred times larger in the actual speckle burst acquisition. The nominal 75 kbit/s rate serving all SO instruments together obviously requires onboard sophistication in condensing images and spectra into maps of physical quantities. In my view, this sophistication must include cross-talk between EUV and visible-light instruments at sub-pixel co-alignment precision and with very elaborate diagnostic quantification.

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REFERENCES

Keller C. U., von der Lühe O., 1992, A&A 261, 321

Rutten R. J., de Pontieu B., Lites B. W., 1999, in T. R. Rimmele, K. S. Balasubramaniam, R. R. Radick (eds.), High Resolution Solar Physics: Theory, Observations, and Techniques, Procs. 19th NSO/Sacramento Peak Summer Workshop, ASP Conf. Ser., Vol. 183, p. 383

Rutten R. J., Hammerschlag R. H., Sütterlin P., Bettonvil F. C. M., 2001a, in M. Sigwarth (ed.), Advanced Solar Polarimetry – Theory, Observation, and Instrumentation, Procs. 20th NSO/SP Summer Workshop, ASP Conf. Ser., in press

Rutten R. J., Hammerschlag R. H., Sütterlin P., Bettonvil F. C. M., van der Zalm E. B. J., 2001b, in A. Wilson (ed.), The Solar Cycle and Terrestrial Climate, Procs. 1st Solar & Space Weather Euroconference, ESA Special Publication SP-463, Estec, Noordwijk, p. 611

Sütterlin P., Hammerschlag R. H., Bettonvil F. C. M., Rutten R. J., Skomorovsky V. I., Domyshev G. N., 2001, in M. Sigwarth (ed.), Advanced Solar Polarimetry – Theory, Observation, and Instrumentation, Procs. 20th NSO/SP Summer Workshop, ASP Conf. Ser., in press