On the co-alignment of solar telescopes. A new approach to solar pointing.

J Staiger
Kiepenheuer Institut, 79104 Freiburg, Schöneckstrasse 6, Germany

E-mail: joe@kis.uni-freiburg.de

Abstract. Helioseismological measurements require long observing times and thus may be adversely affected by lateral image drifts as caused by pointing instabilities. At the Vacuum Tower Telescope VTT, Tenerife we have recorded drift values of up to 5" per hour under unstable thermal conditions (dome opening, strong day-to-day thermal gradients). Typically drifts of 0.5" - 1.0" per hour may be encountered under more favorable conditions.
Past experience has shown that most high-resolution solar telescopes may be affected by this problem to some degree. This inherent shortcoming of solar pointing is caused by the fact that the guiding loop can be closed only within the guiding beam but not within the telescope's main beam.
We have developed a new approach to this problem. We correlate continuum brightness patterns observed from within the telescope main beam with patterns originating from a full disk telescope. We show that brightness patterns of sufficient size are unique with respect to solar location at any instant of time and may serve as a location identifier. We make use of the fact that averaged location information of solar structures is invariant with respect to telescope resolution. We have carried out tests at the VTT together with SDO. We have used SDO as a full disk reference. We were able to reduce lateral image drifts by an order of magnitude.

1. Pointing Systems

Solar pointing systems have to provide for easy and convenient access to solar targets. The pointing precision should match the telescope's resolution. Existing systems fall into two categories which may be distinguished by their feedback properties: Closed-loop and open-loop systems.

1.1. Closed Loop Systems

Closed loop systems require the presence of a full disk telescope (guiding telescope) which has to be physically connected to the primary telescope. The disk center as derived from limb sensors or PSD‘s will define the coordinates system's origin. Opto-mechanical feedback will hold the disk image in place (Fig. 1: VTT Limb Guider).
Examples: Dick Dunn Telescope, NSO Sacramento Peak; Vacuum Tower Telescope (VTT), KIS Tenerife

1.2. Open Loop Systems

Open loop systems do not require specific opto-mechanical pointing components. Solar coordinates are derived from ephemerisis tables and geographical data. Atmospheric refraction effects together with mechanical and thermal telescope properties have to be taken into account by model algorithms. Telescope drive encoders will follow the model data to access a desired target [1]
Examples: GREGOR, KIS Tenerife (Future); ATST, NSO Hawaii (Future)

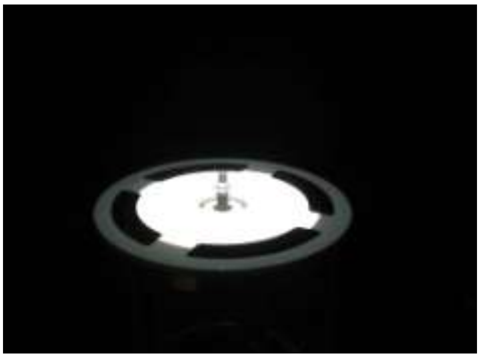

Fig. 1: VTT Limb Guider

Fig. 2: FOV Drift with time

2. The stability- and co-alignment problem.

Spurious image drifts are a common problem with solar telescopes during observations of extended duration. Fig. 2 displays the relative migration of a 50”-by-50” FOV within the primary focal plane of the VTT, Tenerife during 5 hours of observation. The lateral shifts sum up to approx. 10”.
The problem will cause a loss of position and will reduce the effective size of the observing area with time. It may complicate the spatial co-alignment of multiple telescopes as the contributing systems may suffer from the same problem in a non-synchronized way. This will especially be the case when slit-spectrograph observations with narrow footprints are to be synchronized.

If the structures to be observed can be uniquely identified by their instantaneous shape (sunspots, pores etc.), correlation based tools may allow to freeze a region of interest into the viewing area. A most elaborate example for this type of main-beam closed-loop feedback has been developed for SOT telescope onboard space-based HINODE. This unit allowed for image stabilization at a level of below 0.03 arcsec (3 σ) [2]. These unique stability values have been a primary cornerstone for the huge success of HINODE/SOT [3];

Yet the basic problem of establishing a stable and absolute heliographic reference frame within the primary focal plan cannot be resolved by any of the classical guiding means. This is owed to the fact that the only existing quasi shape-invariant fiducial on the sun is the solar limb. Spatial feedback in absolute heliographic terms may thus only be established from full-disk guiding telescopes where the limb is permanently present but not from primary telescopes where this is not the case.
Tight opto-mechanical coupling between the guiding beam and the main beam will partially compensate for these inherent shortcomings. But any shape changes of telescope structure as caused by unbalanced thermal or mechanical loads which are beyond the reach of the guiding beam will not be detected. These undetected loads are a primary source of pointing instabilities and image drifts.

Any project to address this longstanding issue will thus have to find a solution for the following tasks:

- Find main-beam fiducial
- Establish main-beam absolute heliographic feedback.

Journal of Physics: Conference Series **440** (2013) 012004 doi:10.1088/1742-6596/440/1/012004

3. The new approach

3.1. Hypothesis

The instantaneous continuum brightness pattern surrounding a given observational position as viewed by the primary telescope is a unique and unambiguous identifier in determining the absolute heliographic coordinates of this position.

3.2. Stochastic View

The autocorrelation analysis of quiet sun continuum fluctuations lets suggest that adjacent pixels have only a low degree of spatial and temporal coherence when viewed at image resolutions of lower than 1”. This goes back to the irregular and non-predictable distribution of bright granular and dark inter-granular areas across the solar surface.

A probability measure for the occurrence of a specific intensity pattern may thus be derived when assuming a random formation process. It will depend on the number of observed pixels and the range of intensity variations within the digital resolution of the receiver. In the case of a 10-by-10 pixel field and the minimum 2-bit dynamic sub-range for the brightness fluctuations (binary representation) the result would be of the order of

$$P \approx 7.8 * 10^{-29}$$

3.3. Pointing Relevancy

At such low probability levels a pattern may be regarded as to be unique with respect to all other concurrently existing patterns across the solar disk. This should allow for unambiguously locating the primary beam pattern within a simultaneously taken full-disk image. Absolute heliographic coordinate information may then be derived. This in turn may be fed back into a main-beam closed-loop circuit to compensate for any pattern displacements.

4. Technical requirements

Table 1. The following table will give an overview over the opt-mechanical and computational equipment which has to be provided for the new pointing tools:

.

Component	*Requirement*
Main Beam Imaging:	A slit-jaw image (1D or 2D) of the observation field must be provided
Full-disk Imaging	A full-disk image must be provided. Telescope aperture requirements of 10 – 15 cm are sufficient. No mechanical coupling to primary telescope required. No coordinate information from other guiding-telescope required. Telescope may be stand-alone or space-based.

Detectors	CCD camera for slit-jaw image. CCD camera for full-disk image (2K-by-2K or higher).
Networking	Primary telescope and full-disk telescope must be linked for imaging synchronization.
Computing	Real-time pattern processing must be available.

5. Procedural Steps

Several steps have to be taken in sequential order to receive a correctional signal and feed it back into the control loop.

- Take slit-jaw image.
- Take full-disk image.
- Search full-disk for match with slit-jaw pattern.
- Cross-correlate both patterns for closest fit
- Get solar center from full-disk.
- Get offset of full-disk match pattern with respect to solar center.
- Get offset of slit-jaw pattern with respect to full-disk match pattern.
- Add both offsets to retrieve main beam absolute heliographic coordinates .
- Feed back (optional) correctional displacement signal into main beam controls.

6. Test Results with SDO and VTT

A proof-of-concept experiment was carried out at the Izana Observatory, Tenerife in July and October 2012. Continuum data were recorded with the new HELLRIDE instrument [4]. SDO was used as remote full-disk guiding telescope for the new pointing model. SDO web-server time delays required post-facto processing. Performance of the VTT‘s standard limb guider was compared with new system.

Figures 3 and 4 below show stability performance during 5 hours duration. Green circles mark 1“, 5“ and 10“ deviation range with respect to start position. White dot marks instantaneous correlation peak of cross-correlation between full-disk pattern and slit-jaw pattern during final measurement step.

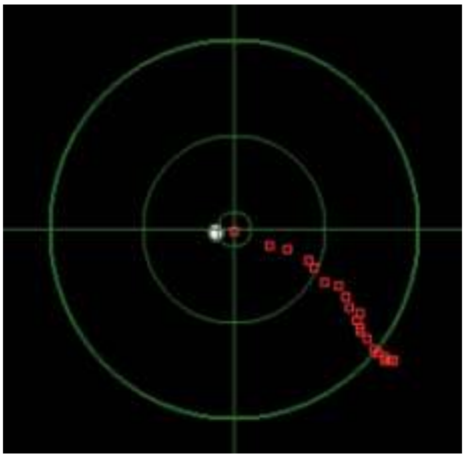

Fig. 3: Stability of "Classical" Limb Guider

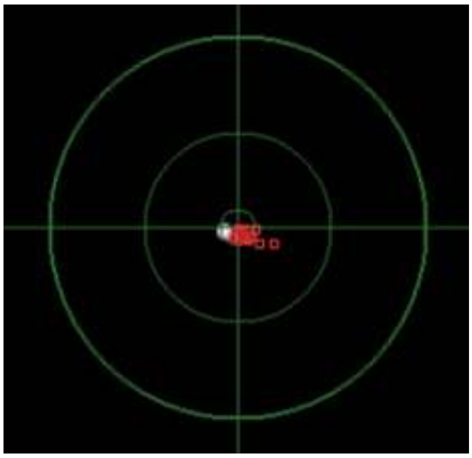

Fig. 4: Stability of New System

7. Benefits

We expect the new pointing model to offer various advantages over existing systems within different fields as listed in the following table

Field	*Possible Benefits*
Engineering	Minimum technical development efforts required. (no mechanical coupling to primary telescope) Frequently used software tools may be applied. Moderate maintenance requirements due to simplicity of system.
Cost	Off the shelf-components may be used (computing, cameras, networking etc.). No customized guiding optics required. Standard astronomical telescope of moderate aperture with standard drives may be used as full-disk guiding telescope. Multiple telescopes may share single guiding telescope
Operational	Precise co-alignment of multiple telescopes possible over extended times Thermal image drifts reduced by appr. order of magnitude Re-adjustment process by more than two orders of magnitude faster than with existing procedures (no main beam limb access required). New approach can be applied to any solar telescope. System may provide input for ‘absolute’ correlation tracking.

Science	High cadence ‘pinpoint’ spectrograph observations possible (‘sit-and-stare’). Determination of precise horizontal flow velocities possible due to ‘absolute’ heliographic pointing. No loss of observational area during long-duration measurements. Precise and fast access to dedicated locations (e.g. flare events etc.).

8. Operation Modes

The new pointing method will allow for a standard drift-compensation mode (slow) and a combined drift/jitter compensation mode (fast). In standard operational mode the cadence for updating the reference full-disk image and the main-beam image will be of the same order and will define the cadence of compensational feedback. We consider an update cadence of the order of 10 to 20 sec sufficient to keep the image motion during this time of below 0.05 arcsec as caused by solar rotation.
The tools may also be used as an add-on to classical guiding.
In fast mode the reference imaging cadence and the main-beam cadence are differing. The main-beam image is now updated at high cadence. The reference image may then be used to detect any rapid image motions to serve as feedback-input to piezo-optics. In this mode the new system would operate as a correlation tracking device freezing the object of interest for the first time into an absolute heliographic framework.

9. Conclusions

We have developed a new approach to solar pointing. It should allow the precise co-alignment of multiple telescopes. New forms of determining lateral velocities in absolute heliographic terms should be possible eg. the recording of the proper motions of magnetic elements within their field environment without the necessity to lock to these elements.
We used SDO and VTT as a proof-of-concept system for the new tools. During an observation campaign in July 2012 we were able to reduce the thermally related image drifts of the VTT by an order of magnitude. Due to a 20-to-40 min. delay in availability of SDO continuum images we have not yet been able to test the system under real-time conditions. We plan to carry out such tests in 2013 at the VTT.
We think that the closed-loop procedures described here will enable us for the first time to continuously span up an absolute heliographic coordinate grid within a solar telescope's main beam which remains in place with time.

References

[1] Wallace P.T., 2006 *ATST Pointing and Tracking PTW/001*

[2] Shimizu T, Nagata S, Tsuneta S. et al., 2008 Solar Physics, **249** 221

[3] Tsuneta S., Itchimoto K, Katsukawa Y et al., 2008 Solar Physics, **249** 167

[4] Staiger J, 2011 *Astron.&Astroph.* **835** 83