AUTONOMOUS CONTROL OF A MOBILE 20-INCH OUTREACH TELESCOPE USING A STAR-TRACKER

Troelz Denver[1),2)], Peter S. Jørgensen[1)], John L. Jørgensen[1)],
Richard Shelton[2)], Edwin Sousa[2)], Joshua Hoblitt[2)], Mike Maberry[3)]
td@oersted.dtu.dk, DTU: +45 4525 3439, IFA: +1 808 932 2390
[1)] Technical University of Denmark, Measurement & Instrumentation Systems,
Building 327, DK-2800 Kongens Lyngby, Denmark.
[2)] Institute for Astronomy, University of Hawai'i,
640 North A'ohoku Place, Hilo, HI, 96720, USA
[3)] Institute for Astronomy, University of Hawai'i,
4761 Lower Kula Road, Kula, HI, 96790-0209, USA

ABSTRACT

We describe a methodology where a fast, lightweight star tracker is attached to a mobile 20-inch telescope and interfaced with the control system to provide encoderless pointing, tracking and guiding for any telescope alignment. The telescope can be quickly deployed for both science and public outreach without specialized alignment.

We describe field tests with an unaligned telescope, where a simple pre-programmed telescope maneuver enables the full telescope misalignment to be determined within a few seconds. The algorithms then continuously provide information at 2Hz about the present misalignment, enabling the operator to mechanically align the telescope if desired, or to track accurately while misaligned.

After initial alignment calibration, the telescope and star-tracker combination provides an absolute telescope attitude that is history independent. This efficiently removes inaccuracies originating from physical and thermal settling, drive biases, etc. This feature is especially useful for closed-loop telescope control. This instrument combination can also perform open-loop sidereal tracking on an unaligned telescope, by using the current attitude to determine the present velocities on the telescope drives.

We present the algorithms and discuss their range of applicability, accuracies obtainable, the rationale for performing various compensations and operational limitations. Finally our experiences and results from extensive field tests are presented.

1. INTRODUCTION

Mobile telescopes offer the possibility of astronomical observation from remote locations where stationary telescopes are not practical. A severe drawback is the typically time-consuming and complicated alignment procedure that greatly reduces observation time. Another drawback is lack of alignment accuracy, which reduces the quality of long exposures.

A star-tracker has previously been mounted on the back of the secondary mirror, and used to control the UH 24-inch telescope on Mauna Kea, creating an optical bench where the orientation between the two boresights remains constant [5]. Attitude from the telescope images are found using the publicly available tool ASCfit [4]. Using data from simultaneous observations with this telescope and star-tracker at various positions, their relative orientation was characterized with high accuracy. We have now realized a similar arrangement with a 20-inch DFM telescope mounted on a mobile carriage, where alignments need to be determined quickly each time it is used.

2. INSTRUMENTATION

The Advanced Stellar Compass (ASC) [2] developed at the Technical University of Denmark, is a three-axis attitude sensor optimized for aerospace, consisting of a fast digital camera with an 18° field of view, a small control computer and full-sky bright star catalog (Fig. 1). Stellar patterns imaged at up to 5 Hz by the camera are autonomously matched for Right Ascension, Declination and Roll at accuracies up to 1 arcsec. The attitude output can be determined in any reference frame while the mount is tracking or slewing at several degrees per sec.

Fig. 1. The Advanced Stellar Compass Star-tracker

The DFM 20” telescope [3] is a small mobile telescope mainly used for outreach purposes offering a 4-meter effective focal length (Fig. 2). It is controlled by a computer program, whose interface allows external setting of the track rates of the two drives in the range –4°/s to 4°/s.

Fig. 2. The DFM 20" telescope mounted on the custom built cart in the car park of the IfA Hilo building

The DFM 20-inch telescope has been mounted on a custom cart built in the IfA machine shop with air-filled wheels for suspension and jacking screws for stability. This cart enables rapid and easy deployment from within a covered building to an open area, providing an easily accessible and stable alignment platform for the telescope drives, and significantly reducing setup time.

3. OPERATION

The star-tracker (fig 1) has been mounted on the back of the secondary mirror of the 20” telescope (figure 1), such that the boresights of the two instruments are coarsely aligned (Fig. 3). The procedures described are designed for operation on the northern hemisphere only. Equations covering the southern hemisphere can be developed accordingly. The two telescope drive axes are expected to be orthogonal. An application for determining orthogonality deviations in the telescope drives is discussed later.

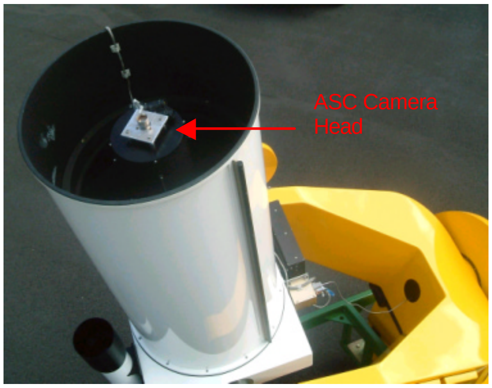


Fig. 3. Top view of telescope with star-tracker camera head mounted on secondary

3.1 Inter-Boresight Calibration

Since the goal is to obtain pointing accuracies in the arcsec range a three-axis inter-boresight calibration is performed between the instrument boresights prior to testing. The result of this calibration is a rotation matrix from star-tracker coordinates to telescope coordinates with arcsec accuracy.

This inter-calibration is found prior to observing from combining star-tracker output with the attitude found from a telescope image. This attitude can be found using the publicly available package ASCfit [4]. Alternatively, the boresights can be accurately aligned mechanically by adjusting the ASC mount to display exactly the coordinates of a bright star imaged in the telescope.

Let a rotation matrix [1] consist of 3 orthonormal vectors: x, y and z each describing the direction of the local axis in a global coordinate frame. Let M_{st} be the star-tracker output rotation matrix describing the boresight orientation in J2000. Let M_t be the telescope orientation found from an acquired image using ASCfit (also in J2000). A matrix defining the rotation from M_{st} to M_t (or M_t given M_{st} as reference frame), M_{ibc} can be found from:

$$M_{ibc} = M_{st}^{-1} M_t = M_{st}^{T} M_t$$

The telescope setup must (obviously) be pointing the same direction while M_t and M_{st} are obtained. Due to the optical bench mount shifts in M_{ibc} will be marginal over time wherefore a calibration on yearly basis is sufficient.

The 3-axis telescope attitude can now be determined with arcsec accuracy from the subsequent star-tracker attitudes by using

$$M_t = M_{st} M_{ibc}$$

3.2 Telescope Alignment

From the mounted star-tracker continuous and accurate information about the telescope 3-axis attitude is available. This information can be used for a fast, accurate and reliable alignment of the telescope drives. Since the inter-boresight calibration has been performed in advance, all star-tracker measurements are automatically converted into telescope attitudes prior to application. Since each measurement is a 3-axis attitude, only two measurements are required. The following procedure is used to establish a full rotation matrix describing the drive misalignment.

1. The telescope is pointed roughly at zenith by moving the drives. Since the telescope alignment is unknown this operation may be carried out manually. The telescope attitude is recorded, denoted M_{zenith}. The timestamp at this measurement is recorded in addition, and acts as reference time for the drive reference frame and subsequent measurements.

2. The telescope is slewed a few degrees “west” using the RA drive. The telescope attitude is recorded, denoted M_{west}.

Throughout the alignment procedure, the telescope tracking is disabled, since the additional compensation for tracking would add complexity to the computation. The full misalignment can now be determined from the two attitudes: M_{zenith} and M_{west}. First of all a compensation for the sidereal drift between the measurements is performed on M_{west}, simply by rotating it according to the timestamp difference. Next, the direction of the telescope drive “north” axis must be the rotation axis between the two attitudes. First the rotation matrix M_{north} is found:

$$M_{north} = M_{zenith} \cdot \left[M_{sid}(-\Delta t) \cdot M_{west} \right]^T$$

where the M_{sid} term compensates for the sidereal motion between the measurements of zenith and west. Next the rotation vector of M_{north} is found: As a consequence of the orthonormality the rotation axis must be the Eigenvector of M_{north} corresponding to the Eigenvalue 1. Alternatively, the vector can be found as described in [1]. Let this vector (in normalized form) be denoted v_{north}. Since this determination can result in a vector pointing south, the sign must be chosen such that:

$$v_{north} \cdot v_{zenith} > 0$$

is satisfied, where v_{zenith} denotes the pointing direction (2-axis attitude) of M_{zenith}. Since v_{north} is the J2000 direction of the telescope north axis, the angular misalignment a_{align} can be found from

$$\cos(a_{align}) = v \cdot \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$$

In order to achieve a continuous observation of the misalignment, a 3-axis coordinate orthonomal frame must be defined for the telescope drive. The north axis has been chosen as the 3rd axis, the rotation of the north axis 90° through zenith is chosen as the 1st axis, and the 2nd axis is chosen to complete the right hand triad. The 2nd axis, v_2, is therefore found from:

$$v_2 = \frac{v_{north} \times v_{zenith}}{| v_{north} \times v_{zenith} |}$$

and the 1st axis, v_1, is found from

$$v_1 = v_2 \times v_{north}$$

An orthonormal rotation matrix, M_{align}, describing the telescope drive 3-axis position in J2000.0 can now be defined as:

$$M_{align} = \begin{bmatrix} v_1 & v_2 & v_{north} \end{bmatrix}$$

Initially, the transformation between the telescope boresight and the drive north $M_{t,d}$ is calculated. This transformation is fixed throughout the alignment phase, since all telescope drives are disabled.

$$M_{t,d} = \left[M_{sid}(-\Delta t) \cdot M_t \right]^T \cdot M_{align}$$

where Mt is the current telescope attitude. The current attitude of the north drive axis, M_{drive}, can now be found from subsequent telescope attitudes, by applying the transformation:

$$M_{drive} = M_{sid}(-\Delta t) \cdot M_t \cdot M_{t,d}$$

In order to get a continuous altitude/azimuth representation of the misalignment a regional reference frame M_{reg} is defined such that zenith is north pole. Such reference frame is obtained, when the initial zenith measurement is used as basis for the frame, i.e:

$$M_{reg} = M_{zenith}$$

All representations in the regional reference frame are compensated for sidereal drift between the time of the measurement, and the timestamp of the frame (the zenith attitude).

The drive north axis orientation in the regional frame, $M_{reg,drive}$, can now be determined from the telescope attitude in J2000 by:

$$M_{reg,drive} = M_{reg}^{T} \cdot M_{drive}$$

The target north axis orientation in regional coordinates, $M_{reg,target}$, is simply the orientation of north in J2000.0 (unit matrix), transformed to regional coordinates

$$M_{reg,target} = M_{reg}^{T} \cdot I = M_{reg}^{T}$$

where I is a 3x3 identity matrix corresponding to the definition of the north axis attitude in J2000. Conversion of $M_{reg,drive}$ and $M_{reg,target}$ into a regional azimuth/altitude representation can now lead to a simple continuous determination of the required residual alignment.

3.3 Unaligned Tracking

The previous section describes the telescope alignment procedure using star-tracker measurements as input. The telescope and star-tracker combination, however, also offers the possibility of performing observation on an unaligned telescope, by changing the track rates continuously according to the current attitude. The field rotation, however, will increase as function of the misalignment as a consequence of the two-axis drive.

First of all, the orientation of the telescope drives must be established, following the 2-step procedure described in the previous section, yielding an orientation of the drives in J2000, M_{align}. Subsequently, when a telescope attitude, M_t, is available it is first transformed into the drive frame, yielding $M_{drive,t}$.

$$M_{drive,t} = M_{align}^{T} \cdot M_{sid}(-\Delta t) \cdot M_{t}$$

The telescope attitude within 1 sec, M_{t+1s}, is extrapolated from the current attitude by rotation at sidereal rate and transformed into the drive frame, yielding $M_{drive,t+1s}$:

$$M_{drive,t+1s} = M_{align}^{T} \cdot M_{sid}(-\Delta t + 1s) \cdot M_{t}$$

By conversion of $M_{drive,t}$ and $M_{drive,t+1s}$ into RA and declination the rates can easily be determined. By applying these rates to the motor drives continuously the telescope boresight will track at sidereal rate and unaligned observation can be performed.

3.4 Unaligned Guiding

The guiding procedure covers closed loop telescope guiding using the star-tracker to measure the current orientation. The target attitude, M_{target}, is a rotation matrix defined in J2000 as a target RA, a target declination and a zero rotation. The attitude can be formed by rotating a unit matrix positive around its 3rd axis according to the RA, followed by a positive rotation around its 2nd axis according to the declination:

$$M_{target} = M_z(RA_{target}) \cdot M_y(90° - Dec_{target})$$

The representation of M_{target} in the drive frame, $M_{drive,target}$ can be found from:

$$M_{drive,target} = M_{align}{}^T \cdot M_{sid}(-\Delta t) \cdot M_{target}$$

The current telescope attitude is also converted into the drive frame, yielding:

$$M_{drive,t} = M_{align}{}^T \cdot M_{sid}(-\Delta t) \cdot M_t$$

By conversion of $M_{drive,t}$ and $M_{drive,target}$ into RA and declination the required distances on each drive can be calculated. If the results are combined with the rates calculated from the unaligned tracking procedure, a simple proportional regulation will be sufficient to guide the telescope without any bias-terms.

4. COMPENSATIONS

In order to enable accurate absolute pointing a number of effects must be considered. These types of compensations have not been included in the measurements performed.

4.1 Atmospheric Refraction

The orientation determined by the star-tracker is based on an acquired digital image. Since the star-tracker does not carry information about the local properties, such as air mass and geospheric location, no autonomous compensation for atmospheric refraction is performed. In order to enable accurate operation away from zenith a refraction model must be included.

4.2 Aberration

The star-tracker is able to perform autonomous compensation for aberrational effect, originating from the geospheric motion and revolution, if information about absolute time and geo-centric velocity is made available. For telescope guiding purposes, however, an orientation relative to the actual star field is preferred. Compensation for aberration effects should therefore not be performed on the star-tracker orientation, at least as long as the inter-boresight angle between the telescope and the star-tracker is relatively small.

5. RESULTS

The algorithms have been implemented in a console program that interfaces directly with the telescope control console over a serial line.

5.1 Telescope Alignment

The console program commanded the motion from zenith going west. After 2 degrees of motion, it was stopped and the telescope drive orientation was automatically calculated. Subsequently, the alignment residual was calculated in an azimuth and altitude representation at 2Hz, and output in the console.

The continuous output of the alignment residual given in delta azimuth and delta altitude enabled a quick motion of the telescope, until the alignment was satisfactory. Fig 4 shows the error between the drive north axis and the true north pole throughout the alignment procedure.

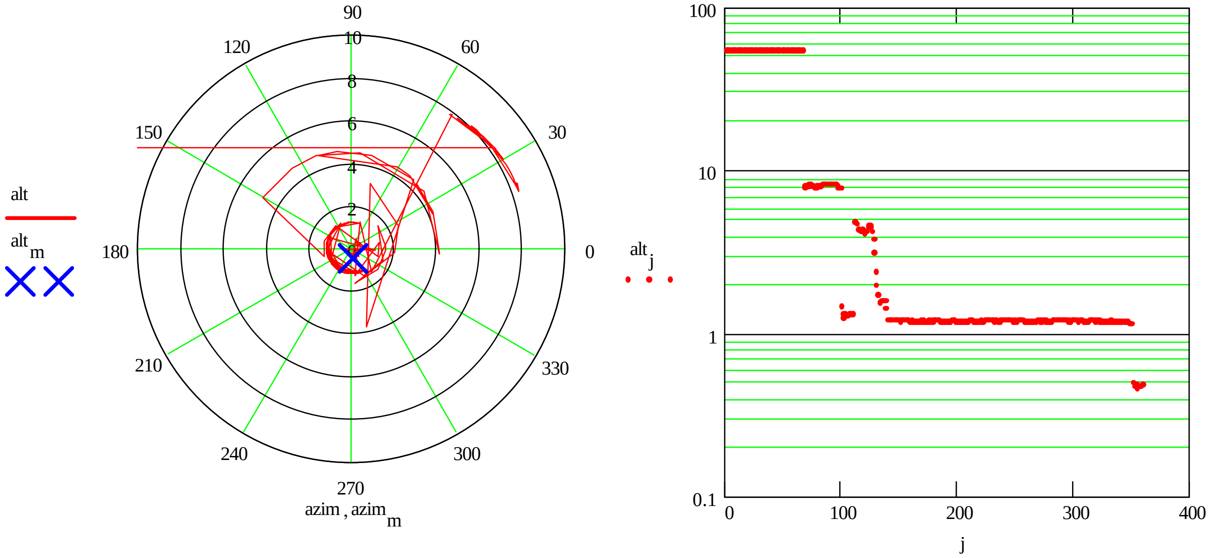
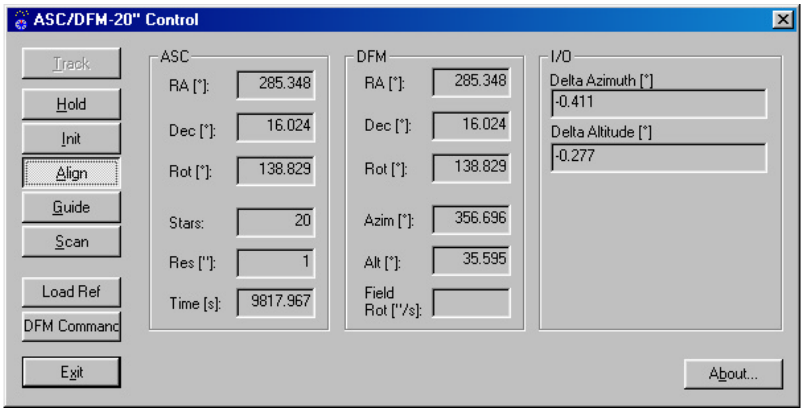


Fig. 4. Left: Polar plot showing the error between the drive north pole and the true north pole in degrees during alignment. The blue cross marks the final position. Right: Logarithmic plot of absolute error between drive north pole and true north pole in arc-seconds during alignment

The azimuth alignment was performed by manually rotating the telescope cart, while the elevation alignment was performed be jacking up the one end of the telescope cart. The achieved accuracy is therefore far from that theoretically possible. Fig .5 shows a screen dump of the console with the final misalignment after the alignment.



ASC

RA [°]: 285.348

Dec [°]: 16.024

Rot [°]: 138.829

Stars: 20

Res ["]: 1

Time [s]: 9817.967

DFM

RA [°]: 285.348

Dec [°]: 16.024

Rot [°]: 138.829

Azim [°]: 356.696

Alt [°]: 35.595

Field Rot ["/s]:

I/O

Delta Azimuth [°]: -0.411

Delta Altitude [°]: -0.277

Fig. 5. Screen dump of console showing the misalignment in the I/O panel

5.2 Unaligned tracking

For a mobile telescope, it is time-consuming and unnecessary to achieve accurate alignment. The unaligned tracking procedure was verified by deliberately placing the telescope system in an unaligned position. The drive orientation (misalignment) was established by commanding the telescope 2 degrees west. The required tracking rates were subsequently calculated at 2Hz from the attitude output from the star-tracker. Fig. 6 shows a world plot of the star-tracker output during the 2 minutes of unaligned tracking. The plot shows, that the telescope boresight remained fairly constant during the test (drift 4 arc-seconds over 2 minutes).

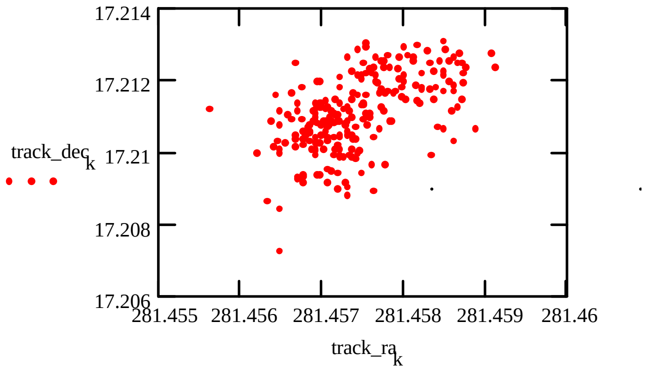


Fig. 6. World plot of the star-tracker output during unaligned tracking

During the sequence, the required motions in RA, declination and rotation was calculated. Since only the RA and declination could be updated by the telescope, a residual field rotation was present. Fig. 7 shows the calculated required motion decomposed in the three components. To prove the versatility of the capability, we have also successfully verified tracking when the telescope N-S axis was aligned approx. E-W.

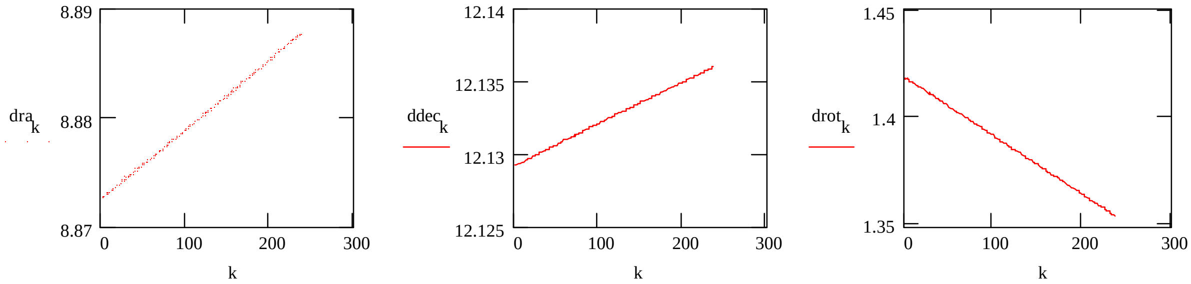


Fig. 7. Plots of the required track rates [arc-seconds/sec] in RA (left), declination (mid) and rotation (right)

5.3 **Unaligned guiding**

The guiding functionality was verified by once again locating the telescope in an unaligned position and commanding the initialization sequence, yielding the telescope orientation. The guiding function was enabled, which offered a combined slew and guide. The target position and the current position was calculated continuously taking the sidereal drift at the given position and alignment into account. The residual motion was commanded to the telescope drives.

During the test different targets was commanded, which enabled automatic slews to the required positions. Fig. 8 shows a world plot of the telescope boresight position during the test sequence. The left graph shows the full guiding sequence with the three targets marked with blue circles. The right graph shows a zoom of the second target being approached and maintained. The bottom graph shows the absolute pointing error in arc-seconds during the entire guiding sequence.

With this mode, object coordinates can be entered into the RA/Dec target entries. The telescope slews there and acquires the object in the cassegrain field. The new feature is that this can be done accurately and repeatedly on an unaligned telescope.

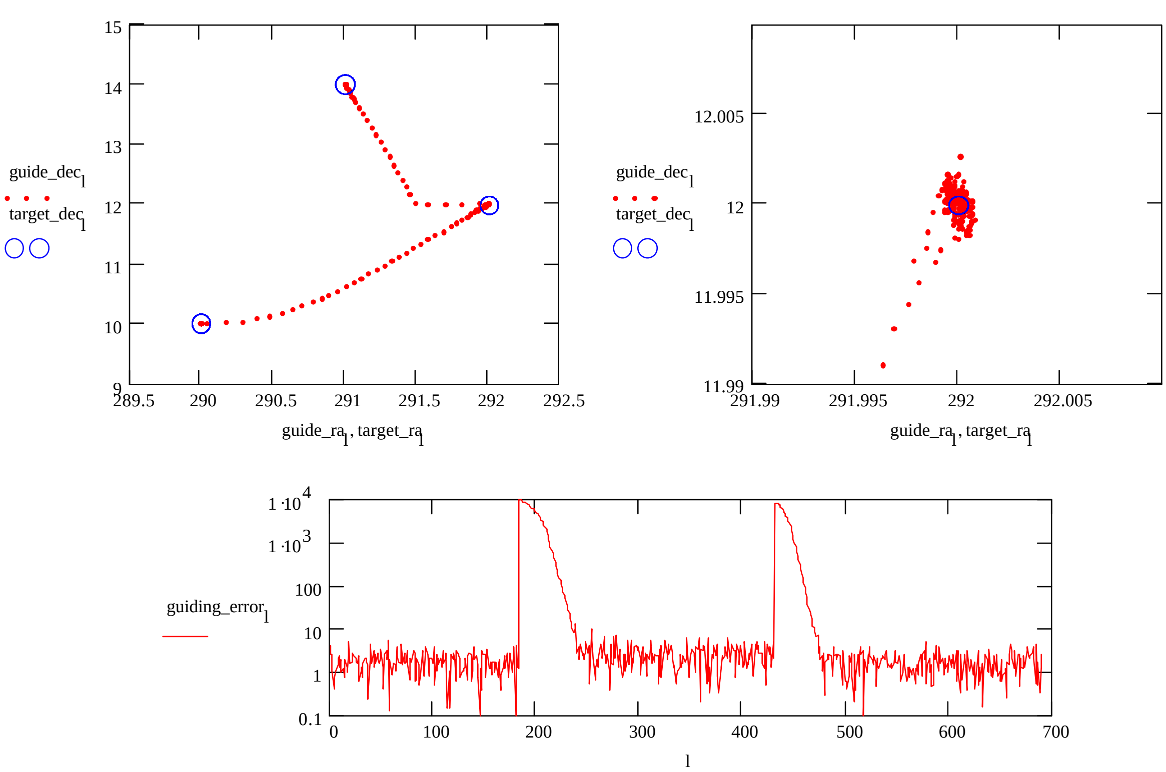
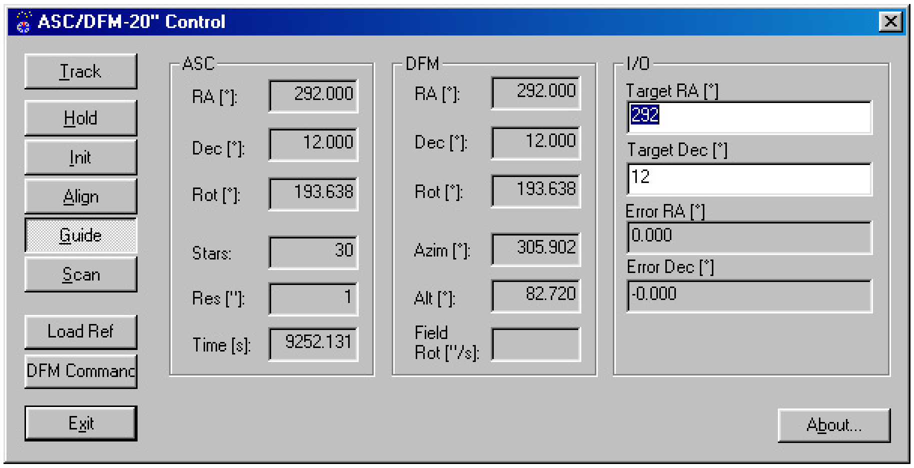


Fig. 8. World plot of the star-tracker output during unaligned guiding. Left: The full guiding sequence with the three targets marked with blue circles in degrees. Right: Zoom of second target being approached and maintained (in degrees). Bottom: Log graph of the absolute error during the measurements (in arc-seconds).

Fig. 9. shows a screen dump of the console, showing the target and the current errors



ASC

RA [°]: 292.000

Dec [°]: 12.000

Rot [°]: 193.638

Stars: 30

Res ["]: 1

Time [s]: 9252.131

DFM

RA [°]: 292.000

Dec [°]: 12.000

Rot [°]: 193.638

Azim [°]: 305.902

Alt [°]: 82.720

Field Rot ["/s]:

I/O

Target RA [°]: 292

Target Dec [°]: 12

Error RA [°]: 0.000

Error Dec [°]: -0.000

Fig. 9. Screen dump of the console program during guiding

6. CONCLUSION

A star-tracker has been mounted on the secondary mirror of a small mobile outreach telescope creating an optical bench maintaining their relative orientation. The functionality of this setup has proven to be extremely efficient for a fast and accurate telescope drive alignment. An alignment error of 0.5° was achieved after a few minutes. Since the telescope is used for demonstration purposes only, this accuracy is by far sufficient. A higher accuracy can be achieved, by development of a more sophisticated mechanical alignment device.

Additionally, experiments were carried out performing sidereal tracking on the unaligned telescope, using the star-tracker measurement to set and update the tracking velocities continuously. The system maintained the current line of sight for a long period of time, with a small pointing drift in the range of 30marc-seconds/sec, supposedly due to either mechanical/thermal settling of atmospheric refraction.

Finally, experiments were carried out performing closed loop guiding at different targets using the star-tracker output. The targets were approached and maintained with high accuracy.

The combination of a star-tracker and a telescope has proven to be highly efficient in telescope setup and tracking.

7. FUTURE APPLICATIONS

Absolute orientation knowledge about the telescope position relative to the telescope drives, as offered in the telescope and star-tracker combination, can be used in a high variety of applications. The procedures described in this paper are only a short subset of this extensive list. The following applications are ideas that easily can be realized with the current setup.

7.1 Telescope Drive Non-Orthogonality

The initial alignment determination was established from a motion in RA alone, expecting that the telescope drive axis were orthogonal. If motions in RA are combined with motions in declination, high accuracy characterization of the drive orthogonality deviation can be achieved.

7.2 Local Orientation Dependency

Shifts in the telescope mirror cells dependent on the local orientation can cause deviations in the apparent telescope boresight. By combining orientations of telescope images with star-tracker measurements in a large number of orientations, a regional characterization of this effect can be established. This characterization can be included in the conversion algorithm from the star-tracker to telescope boresight to increase the pointing accuracy further.

7.3 Non-Sidereal Tracking

The star-tracker can optionally be set to output positions of celestial objects that are not recognized as stars, such as planets, comets, satellites, etc. This information can be used as guiding information to the telescope, in order to perform closed loop non-sidereal tracking.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. J.R. Wertz: "*Spacecraft Attitude: Determination and Control*", 1994, Kluwer Academic Publishers, ISBN: 9027712042
2. J. Jørgensen & C. Liebe: "The Advanced Stellar Compass, Development and Operations", *Acta Astronautica IAA International Symposium on Small Satellites for Earth observation 4-8 November, Vol. 39, Berlin*. Pp 775-783, Pergamon, 1997. For information on Advanced Stellar Compass star-tracker: http://server4.oersted.dtu.dk/research/ASC/index.html
3. For information on the DFM telescope: http://www.dfmengineering.com/cct_20.html
4. Jørgensen, P.S., Riis, T., Betto, M. & Pickles, A.J.: "*ASCfit -- Automatic Stellar Coordinate fitting package*", Astronomical Data Analysis Software & Systems XI (Victoria, 2001). ASCfit available at: http://www.ifa.hawaii.edu/~pickles/AJP/ascfit.ps.gz
5. Jørgensen, J.L. & Pickles, A.J.: "*Fast and Robust Pointing Using a Second Generation Star-Tracker*", SPIE 3351, 07 (1998)