Revision 1, Answers to Review Comments: "A Novel Framework for Automatic Scanning Radar Pointing Calibration Using the Sun"

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Preface

We thank all three reviewers for taking the time and effort for reading our manuscript in detail. All of those are valuable comments and raise interesting questions. We tried to answer each point as well as possible.

Structure

This document contains up to three items for each review comment. **Comment** contains the original comment by the reviewer. **Response** is our response to the comment, explaining our thoughts and decisions. Optionally, **Changes to manuscript** lists the most important adaptations to the manuscript with regard to this comment, if not already mentioned in the response. Line and figure numbers refer to the submitted version of the manuscript, if not stated otherwise. For a full list of changes, please also have a look at the provided 'latexdiff' document, showing all differences between the submitted and revised version of the manuscript.

Contents

Reviewer 1

General Comments

R1.1 **Comment:** Although I commend the authors on readability given the technical nature of the manuscript, I think the visual presentation could be improved. Figures should be understandable "at first glance". At the moment, some figures need quite some time to fully take in. Readers should know what is shown with the figure caption alone and all parameters / abbreviations should be clear. I understand that due to the content, many parameters are necessary and it might be too detailed to list all in each figure. For efficiency, something along the lines of "for nomenclature, see text" could be added to the respective captions. Also, subpanels should be labeled consistently across the manuscript. Some text (e.g., parameters in Fig. 1) are very small. Please double check if everything is readable in a realistic size at 100%. Multiple figures could be improved in my opinion to make the paper more accessible / easier to follow. I find it hard to read the colorbars in Fig. 4 (see specific comments). I would argue that Fig. 5 is not clear enough and should include labels of angles / parameters or be more explicit what the arrows show. I wonder if Fig. 9-11 could be combined into one; or possibly 10-11. I also think that Fig. 15 could be adapted to increase readability. For example, it could be noted in the figure what the boxes represent and the text corresponding to blue arrows could be color-coded blue as well such that is clear what text belongs to where. Currently at first glace everything blends together and it takes quite long to follow the flow / logic of the figure. I think there's room to improve without too much work.

Response: Thank you for the constructive feedback on the figures! We will go through it stepwise.

(a) Fig. 1: We enlarged the parameters.

(b) Fig. 4: See item R1.9.

(c) Fig. 5: We improved the caption and added a color gradient, see Figure 3.

(d) Fig. 9-11: We combined them into one figure. We also included a reference arrow, which acts as a scale for the pointing difference. We made the caption more comprehensive and hopefully easier to understand.

(e) Fig. 15: We added more descriptive text to the figure, color coded some texts, made the caption more comprehensive and point to the list of symbols at the end of the manuscript.

R1.2 **Comment:** It is not clear to me what the limitations of the approach in terms of latitude / seasonality are if any. Can you include recommendations and/or make it explicit whether this can be applied for example in polar regions? Given the dependence on sun elevation, I assume there might be ambiguities, but maybe this is no issue.

Response: This is an interesting point! Generally, we can only infer information about a specific parameter from a Sun scan, if the Sun is located in a position of the sky, where the pointing is sensitive to the parameter. We therefore simulated the mispointing for each (static) scanner parameters for all positions in the sky in Figure 1. The markers in each panel show the Sun position for Munich and a polar location (Neumayer Station at 69°40'S, 008°16'W). As we see, in Antarctica, the Sun traverses through at least one sensitive region for each parameter, except for the gimbal tilt β. Consequently, we expect that all parameters except β can also be estimated in polar regions, with only information from low Sun elevation angles available. For campaigns and mobile radars, probably by far the most important parameters are the pedestal

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tilts α and δ. For their estimation, as also described in Sec. 2.3. in the manuscript, samples close to the horizon in the West and East or North and South, respectively, are sufficient. However, once we approach polar night and the Sun is located in the North or South only, we expect that α cannot reliably be estimated anymore, since there is no sensitivity to this parameter close to the horizon in the North or South (Figure 1a).

This discussion applies similarly to seasonality, obstacles in the radar surrounding or limitations in the radar mechanics, which inhibit Sun scans in certain sectors of the sky.

Changes to the Manuscript: We added a corresponding section to the discussion of the method. We also reference the new figures in the methods section.

Specific Comments

R1.3 **Comment:** Line 25: as is common in the higher atmosphere – include a reference

Response: Added!

R1.4 **Comment:** Line 38: The benefits of solar calibration are now widely acknowledged – I would also expect some references here

Response: Added!

R1.5 **Comment:** Line 75: applicable by – is that the right English term? I'm also not a native speaker

Changes to the Manuscript: Changed to: "To make this methodology accessible to the broader community, ..."

R1.6 **Comment:** Line 83: since SunscanPy is first mentioned here: I would recommend to publish the code on Zenodo or similar to get a DOI. It can then be directly referenced here

Response: Good suggestion! See `https://doi.org/10.5281/zenodo.18862011`

Changes to the Manuscript: We added the zenodo citation in line 83 and also in the code availability section.

R1.7 **Comment:** Line 177: Out of curiosity, how accurate is it to model the solar emission pattern as a bipartite function? Maybe include some references

Response: Please see the answer to item R3.11

R1.8 **Comment:** Line 185: What about other radar systems?

Response: We can not give a general answer for other radar systems, it depends on the sensitivity of those. However, if a system is sensitive enough to actually detect the sky emission, it would be quite easy to implement this in SunscanPy. Just set H_0 (the sky contribution) to the value determined from the sky samples. For the noise, you might assume $H_n = 0$ in this case.

R1.9 **Comment:** Figure 4: (1) insensitive – do you mean less sensitive? (2) grey-white colorbar – I get the idea, but I can't tell when it is blue / yellow which greyscale that corresponds to. can you please include blue and yellow color bars instead? (3) I understand the red line is the expected signal resulting from background, beampattern, and sun. However, I find it unintuitive how you depict this currently, since you show a discrete colorbar with 0.0 and 1.8

dB and draw 0.8 in the middle. I suggest to remove and only keep in the figure caption or find a more intuitive way to include in the plot.

Response: (1) Changed accosdintly! (2) Note that the central panel a) of the figure is meant more as a qualitative illustration. We want to provide the reader an impression what a beam opening angle of 0.5° actually means with respect to the solar disk. We also want to illustrate our method, which is based on a bi-valued function for the sky, overlaid with a continuously varying beam pattern. We acknowledge that reading quantitative values from the central panel is difficult; however, this is not the intended purpose of the figure. The quantitative convolution of the sky radiance distribution and the beam pattern is computed by SunscanPy. (3) We removed the red line and included the value in the figure caption instead.

R1.10 **Comment:** Line 254: Nelder-Mead simplex optimization – can you include a reference?

Response: Included!

R1.11 **Comment:** Line 260: How many scans do you recommend to average?

Response: We see the scattering of those quantities between subsequent scans in Fig. 9 (formerly Fig. 8) in the manuscript. For our case, we can average the azimuth backlash over all scans of the day, while the time offset, which shows a weak linear trend with respect to solar elevation, could be represented by e.g. a linear regression, if very high precision is required. However, for practical applications, we would recommend to simply average over all available scans of the day in both cases.

R1.12 **Comment:** Line 305: small number of samples – please be more explicit. How many are a small number?

Response: In this case, we collected 5 samples. We added this information to the manuscript.

R1.13 **Comment:** Footnote page 15: I would also include a link to the specific data you used using the custom DOI feature of cloudnet (at least in the data availability section)

Response: Actually, the sun scans are not available on Cloudnet. We just wanted to point out here, that Munich is a Cloudnet site and the continuous measurements of this instrument are available on Cloudnet. An example dataset of a Sun scan, as we used in the manuscript, is contained within SunscanPy at `https://github.com/Ockenfuss/sunscanpy/tree/main/sunscan/examples`. The tutorial notebook, part 1, gives an example how to load the raw data and process it.

Changes to the Manuscript: We clarified the footnote: "Continuous measurements and derived products..."

R1.14 **Comment:** Figure 9: the grey lines should also be included in the legend

Response: See the general rework of the figure in item R1.1.

R1.15 **Comment:** Line 430: I had a look at the tutorial notebooks (very nice!). Maybe it would help to also include a sketch with the different angle/parameter definitions in part 1

Response: Thank you, we appreciate that you took the time to look at them as well! You mean a sketch like Fig. 2 in the manuscript? We can think about that, but since those angles actually appear for the first time in part 2, we included the figure there. (The figure is also on the start page of SunscanPy now).

Technical Corrections

R1.16 **Comment:** Line numbers: there are more than 5 lines between 90 and 95. Please correct to make the review process easier in case there is a second round after revisions.

Changes to the Manuscript: Corrected!

R1.17 **Comment:** Equations: Please check the punctuation after equations (e.g., 1, 2, 9, 10, 13, 14). I would also give MP: $(\gamma, \omega) \to (\phi, \theta)$ a number, or put in text.

Response: Corrected!

R1.18 **Comment:** Line 3: particle's – particles'

Response: Corrected

R1.19 **Comment:** Line 80 and onwards: Section instead of section

Response: Corrected!

R1.20 **Comment:** Line 8:1 sun – be consistent if sun or Sun

Response: Changed consistently!

R1.21 **Comment:** Figure 4: puse – pure

Response: Changed!

R1.22 **Comment:** Line 285: period at the end missing

Response: Changed!

R1.23 **Comment:** Figure 10: has an "a" label, although there are no other panels.

Response: Corrected!

R1.24 **Comment:** Line 428: piplines – pipelines

Response: Corrected!

R1.25 **Comment:** Line 455-456: fix citation style (remove brackets around year)

Response: Corrected!

R1.26 **Comment:** Line 530: aw – as

Response: Corrected!

Reviewer 2

General Comments

R2.1 **Comment:** You mention there being no general radar agnostic framework for Sun scan data. The Rave toolbox contains radar agnostic code for finding solar hits in weather radar volume scans. I think you need to set up that your method uses solar box scans rather than opportunistic hits before this statement to be clear what you mean by "Sun scan data" and then I believe your statement would be correct.

Response: We clarified the sentence: "... there is no general, radar-agnostic framework to calibrate the pointing from Sun scans." Actually, our data pipeline starts once the Sun observations are available. In this sense, it could probably be a nice complement for RAVE, which finds the solar observations in general volume scans. However, you are right that in this manuscript, we only apply SunscanPy to dedicated box scans. Up to now, we have not tested the applicability of SunscanPy to a collection of opportunistic hits.

R2.2 **Comment:** The closest analogue I can find to your approach in the literature is that of Muth et al, 2012 but I note some differences. Can you explain how your 7 static parameters map to the 6 used by Muth? I note in particular that you describe ϵ as offset from the elevation rotation of the scanner, and state at beam pointing close to the horizon it causes only an azimuth offset, while Muth defines two parameters, one in azimuth and one in elevation that model the collimation offset (which seems analogous to your ϵ) given your schematics. What is the advantage of your parameterisation approach compared to that of Muth et al? In some ways I see your ω_0 may be analogous to their elevation collimation offset but clearer diagrams would help in this regard.

Response: Yes, you are right! We only have one parameter ϵ for the antenna tilt (or "collimation offset" in terms of Muth et al. [2012]), since the other antenna tilt direction is already accounted for by an offset in the elevation axis, ω_0. An additional "antenna elevation tilt" parameter could not be distinguished from the elevation axis offset and is also not necessary to fully describe the system, if an elevation offset is already present. As far as we see, the convention by Muth et al. [2012] and our convention both describe the *static* scanner system completely. We have one parameter more since we also include the *elastic* bending of the system with the parameter χ (not counting the additional *dynamic* parameters). For the azimuth axis, it is very common to speak of an "azimuth offset" or a "northangle". Therefore, we decided to apply this nomenclature consistently to the elevation axis as well, in the form of an elevation axis offset, rather than a beam collimation offset.

R2.3 **Comment:** I also note that you also only model backlash in the azimuth axis. What about in the elevation axis? Many radars perform RHI scans, and therefore the impact of scanning velocity in the elevation axis should also be considered. I presume this would need a different box scanning approach that scans in azimuth steps rather than elevation steps. This would impact section 2.2.2 in terms of how to set up box scans.

Response: Good point. You are right that an elevation backlash would likely require azimuth steps with different speeds in the scan to distingish it from a receiver-scanner time offset, similar to the azimuth axis. Note that the time offset affects the elevation axis as well and is included in our model (Section "Scanner inaccuracies": $\tilde{\omega} = \omega + t_0 \dot{\omega}$), so there is a velocity dependency in the elevation axis. From our experience and communication with the manufacturer, we learned that in the elevation axis, there is usually no backlash. This is because the radar is rarely in perfect balance along this axis and gravity usually pulls the elevation axis into either the forward or backward direction, if there is some play in the gears. For the azimuth axis, the effect of gravity is much weaker, since this axis is (approximately) aligned with the direction of gravity. Conceptually, it would be straightforward to implement an elevation backlash in SunscanPy, if this is relevant for a future application. Probably, in this case a clever "diagonal" scan strategy can be used to determine both backlashes even from a single Sun scan.

R2.4 **Comment:** Section 2.2.3 – can you cover the implications for radars which can not scan over vertical? I know of some that are mechanically limited and can't exceed a given elevation

angle, let alone do a 180 degree hemispheric scan. Which parameters can still be estimated, which can't? Does this matter?

Response: Interesting point. We included a new figure to show the sensitivity of different parameters at different locations in the sky: Figure 1. The discussion in item R1.2 also applies to a restriction in scanning angle. As we can see, all parameters except β can be well estimated from the lower elevation angles alone. However, as we discuss in the new "Dependence on Latitude and Seasonality" section in the manuscript, without the reverse scan, some parameters can not be estimated independently.

Changes to the Manuscript: Please see the new "Dependence on Latitude and Seasonality" section in the manuscript, Figure 1 and item R1.2.

R2.5 **Comment:** Figure 5 – this isn't very clear, though I appreciate what you are intending to show. Maybe make the radar asymmetric to highlight the difference between forward and reverse more clearly. Or include errors to show how they relate to the antenna position.

Response: We included a color gradient and a small box to the radar to make the orientation more intuitive.

Changes to the Manuscript: See Figure 3

R2.6 **Comment:** Section 2.3 – more information about the latitude limitations here, and what you mean by the course of a full day in the summer months in terms of solar positions. Your abstract talks about the benefits for research campaigns, which are often short duration, not in summer and could be at a range of latitudes so it would be good to know what the requirements are. Thinking back to radars which cannot scan over vertical, how do these requirements change compared to a fully steerable antenna?

Response: Please see our response to item R1.2.

R2.7 **Comment:** Figure 8 – Consider plotting vs solar azimuth rather than elevation.

Response: While azimuth would display the points in the correct temporal order, we decided to plot against elevation, since this determines the atmospheric path length and the intensity of the solar signal.

R2.8 **Comment:** Figure 9 – These aren't very informative, especially given the need to magnify errors on the second plot. Consider using plots similar to those in Fig 8 instead, using solar azimuth. Changing the size or intensity of the colour as a function of solar elevation could also add in showing that dependency.

Response: We reworked Fig. 9/10/11. Those are now combined into one, have a much more extensive caption and a reference arrow in each magnified plot to act as a scale. This way, the quantitative pointing difference can be read from each plot.

R2.9 **Comment:** L453 – Here you discuss the potential for retrospectively improving datasets. Could you provide more detail about what would be required. I suspect most legacy datasets don't have an archive of solar box scans available to reprocess, so what can realistically be done?

Response: There are several possibilities. If the radar is stationary and mounted to a solid surface (concrete, building roof), Sun scans can be performed now and the resulting coefficients can be applied in retrospect until the time when the radar was last moved. Also, since Sun scans itself are not new (see Introduction), there may be Sun scans available even in legacy

datasets. They can be reevaluated using our toolbox, which includes a very comprehensive scanner model, compared to earlier approaches. Last, but not least, random solar hits in regular scans could potentially also be evaluated using our tools, although we have to acknowledge that so far, we have not tested this approach and it is beyond the scope of the current manuscript.

Changes to the Manuscript: We clarified the sentence: "`SunscanPy` makes it possible to monitor pointing accuracy over long time scales, or, if the scanner configuration is assumed to be stable over time, to retrospectively improve the pointing accuracy of existing datasets."

Minor Corrections

R2.10 **Comment:** L2 – change "cloud" to "clouds".

Response: Corrected!

R2.11 **Comment:** L3 – change "retrieve particle's vertical motions" to "retrieve the vertical motion of particles".

Response: Corrected!

R2.12 **Comment:** L11 – remove "the" between "facilitate" and "automatic".

Response: Corrected!

R2.13 **Comment:** Can it work with non-stationary radars? If not, reword L12 sentence.

Response: A full calibration takes one day. Therefore, it does work for any radar, which is sufficiently stationary that a set of constant calibration coefficients is valid for at least a couple of days. It will not work on a ship or moving truck, where the radar considerably moves within one Sun scan series (i.e. one day). However, it should work well for a radar on a parked trailer, truck or sledge.

R2.14 **Comment:** L21 – "displacement at a distance" rather than "in".

Response: Corrected!

R2.15 **Comment:** L34 – "alternative is to use the Sun".

Response: Corrected!

Reviewer 3

R3.1 **Comment:** The concept of inverse kinematics is mentioned several times but it is never explained. Please provide a brief explanation.

Response: Inverse kinematics describes the problem of determining the joint positions of a kinematic chain, given a desired location and orientation of the chain end (or, in our case, determining the axes positions given a desired antenna orientation). We added this to the manuscript.

R3.2 **Comment:** Lines 26 - 27: Please provide references for the velocity figures, including the precision of the velocity measurement.

Response: Included!

R3.3 **Comment:** Lines 60 - 61: It should be mentioned that the sun is also used as source for receiver noise calibration.

Response: Do you mean in the specific publication mentioned in this line [Reimann and Hagen, 2016], or in general?

R3.4 **Comment:** Lines 67 - 68: "Second, existing calibration workflows typically assume that mechanical correction of the scanner is required once biases are identified". This requires clarification. "mechanical correction" would mean that the sensor measuring the angle of the respective axis would have to be adjusted to a kind of "zero position". However the digital encoders of modern weather radars are only calibrated with digital offsets. A manual mechanical correction or adjustment would be to expensive. If "mechanical correction" refers to the alignment of the pedestal, like in Fig. 1/3 please refer to e.g. shipborne weather radar antennas, which have to compensate the movement of the ship permanently for pitch, roll and yaw. This is nowadays all done by software using a gyro as reference.

Response: Our expertise lies mostly in the field of cloud radars. Here, an actual mechanical adjustment like the mechanical leveling of the pedestal is indeed common and state-of-the-art. Some cloud radars also have inclination sensors to detect the orientation of the dish with respect to the Earth's gravitational field. From our experience, the difficulty with this approach is the mounting and calibration of the sensor. For example, if the sensor is mounted in the elevation box (see the scanner drawing in the manuscript), an antenna tilt ϵ would go unnoticed. In comparison, the Sun scan technique provides an end-to-end calibration, where the deviations are derived from the actual beam pointing of the radar. Concerning ship borne radars, our method currently does not support them. Maybe, it can be extended in the future. For a ship borne radar, it will certainly be much more difficult to connect many Sun scans over the course of one day, while the ship is moving. In any case, the biggest source of uncertainty in the pointing of a ship borne radar might be the uncertainty in the orientation of the ship, for which we can obviously not derive a correction factor, since it is constantly changing over time.

R3.5 **Comment:** Lines 90 -95: The line numbering is incorrect. There are more than 5 lines.

Response: Corrected!

R3.6 **Comment:** "$\theta \in [0°, 90°]$", "$[0°, 180°]$": Negative elevation angles are not unusual, in particular for shipborne radars. The method presented in this paper should take this into account.

Response: Good point. The method works perfectly for γ and ω outside of the given ranges. In SunscanPy, we currently allow for axis positions up to 20° below the horizon (-20° to 200° for ω). We removed the limits for γ and ω here. Note that, by definition, ϕ and θ, which are spherical coordinates, are still limited to $[0°, 360°]$ and $[0°, 90°]$, respectively.

R3.7 **Comment:** With respect to the degree of accuracy which the authors intend to achieve: Is it necessary to consider the offset of the phase center of the antenna with respect to the Az and El rotation axis?

Response: Very good point! Since the sun is sufficiently far away, spatial offsets of the antenna have no effect on the pointing, only the orientation matters. Internally, when building the kinematic chain to model the scanner in the SunscanPy library, this allows to set the spatial separation between the joints to zero and treat the problem purely as a series of rotations.

R3.8 **Comment:** Line 116: The backlash does not depend on the velocity but on the direction of rotation, as correctly addressed in line 214.

Response: In our formulation, backlash depends on the velocity, but only via the sign function (which indicates the direction of rotation). This is probably a matter of perspective.

R3.9 **Comment:** Line 170: The reference does not mention the Airy pattern. However Chapter 10-8 discusses patterns of large aperture antennas with uniform illumination which causes an Airy pattern. But parabolic reflector antennas are normally using a tapered illumination to keep the sidelobes low. The authors should explain why they use the Airy pattern and not the Gaussian pattern, which is normally applied, which resembles the tapered illumination better, and which is therefore also used in the derivation of the meteorological radar equation.

Response: During the development of SunscanPy, we started with a Gaussian pattern. Subsequently, Metek, the radar manufacturer, pointed out that in some of their sunscans, they were able to see the effect of the first side lobe when scanning a large enough pattern around the solar disk. Therefore, we took the Airy pattern as a first approximation of an antenna pattern, which includes side lobes. However, from our experience, the effect on the derived pointing is small to negligible. Both patterns are radially symmetric and since we do the fit in linear space, the main lobe dominates the result. Both the Gaussian and the Airy pattern have an almost identical shape for the main lobe, as can be seen in Figure 4a. Figure 4 also shows a measured antenna pattern, provided by Metek. Note that this measurement might not represent the actual antenna pattern perfectly, since nearfield effects are still present in the measurement (taken at 160 m distance from the antenna). For the case where SunscanPy is applied to a radar which needs a special patterns (not Gaussian/Airy), SunscanPy is written in a way that the antenna pattern can be easily changed.

R3.10 **Comment:** Line 177: Please explain this expression. Probably "bivalued" function is meant.

Response: Yes, this is the correct word.

R3.11 **Comment:** There are several publications discussing the center-to-limb variation of the microwave radiation of the sun, e.g. Shibasaki, K.:"Microwave Observations of the Quiet Sun", Solar Physics with Radio Observations, Proceedings of Nobeyama Symposium 1998, NRO Report 479. The authors should address the error caused by neglecting this effect.

Response: This is an interesting point. In the process of developing SunscanPy, we actually included a factor to vary the solar disk brightness towards the limb by a few percent and included it in the optimizer. However, we found no significant improvement in the fit quality or significant changes in the derived pointing. According to Selhorst et al. [2003], the increase can be up to 20% near the solar poles, but the brightening region is confined to the outermost limb of the disk. Note also that all symmetric (with respect to the solar disk center) deviations of the solar brightness from our model would likely not bias the derived pointing. However, we acknowledge that in the future, parameterizations of the solar limb brightening could be implemented in SunscanPy. The technical foundation for such an adaption is already contained in the package.

R3.12 **Comment:** Line 211 - 212: How do you prevent the sun from being received by an antenna side lobe? Or is this not critical since you are only looking for a large difference?

Response: Yes, we are recommending to simply take the sky noise sample sufficiently far from the sun to avoid catching an antenna side lobe.

Changes to the Manuscript: We clarified this in the manuscript.

R3.13 **Comment:** Line 564 - 565: The reference is not clear. The international issue of the 3rd edition of the book was published in 2002, the US version in 2001. A reprint of this edition

was published as paperback or softcover later, but the copyright is still 2002. Moreover, page 986 is the first page of Appendix B. Why do the authors refer to the appendix?

Response: We have corrected the citation. The formula for the beam pattern of a parabolic reflector can be found in chapter 12.7. in the book.

References

X. Muth, M. Schneebeli, and A. Berne. A sun-tracking method to improve the pointing accuracy of weather radar. *Atmospheric Measurement Techniques*, 5(3):547–555, 2012. doi: 10.5194/ amt-5-547-2012. URL https://amt.copernicus.org/articles/5/547/2012/.

J. Reimann and M. Hagen. Antenna pattern measurements of weather radars using the sun and a point source. *Journal of Atmospheric and Oceanic technology*, 33(5):891–898, 2016. doi: 10.1175/ JTECH-D-15-0185.1.

C. L. Selhorst, A. V. R. Silva, J. E. R. Costa, and K. Shibasaki. Temporal and angular variation of the solar limb brightening at 17 ghz. *Astronomy & Astrophysics*, 401(3):1143–1150, Apr. 2003. ISSN 1432-0746. doi: 10.1051/0004-6361:20030071.
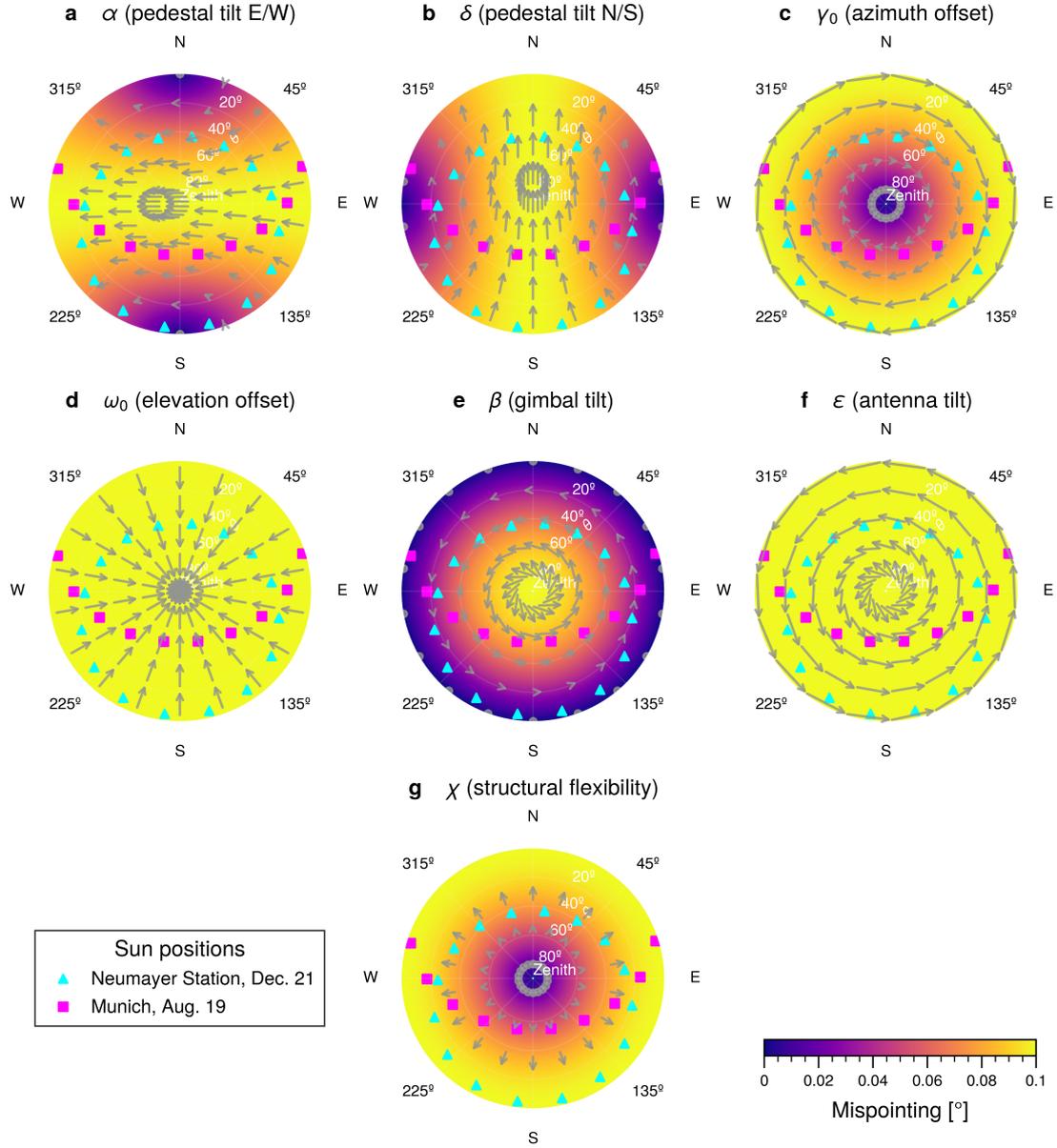
Figure 1: Mispointing caused by the static scanner parameters, as a function of position in the sky. Each panel shows the effect of a change in the corresponding parameter of 0.1° (χ: -0.1°), the other parameters are kept at 0.0°, respectively. Shown is the forward scanner configuration. The markers show the path of the Sun for Munich and an Antarctic location (Neumayer III station at 70°40'S, 008°16'W). The arrows show the direction and magnitude of the mispointing (magnitudes enhanced). Reading example for panel **d)**: An elevation offset of 0.1° causes a constant mispointing of 0.1° everywhere in the sky (colormap). The mispointing is always directed towards zenith (arrows).
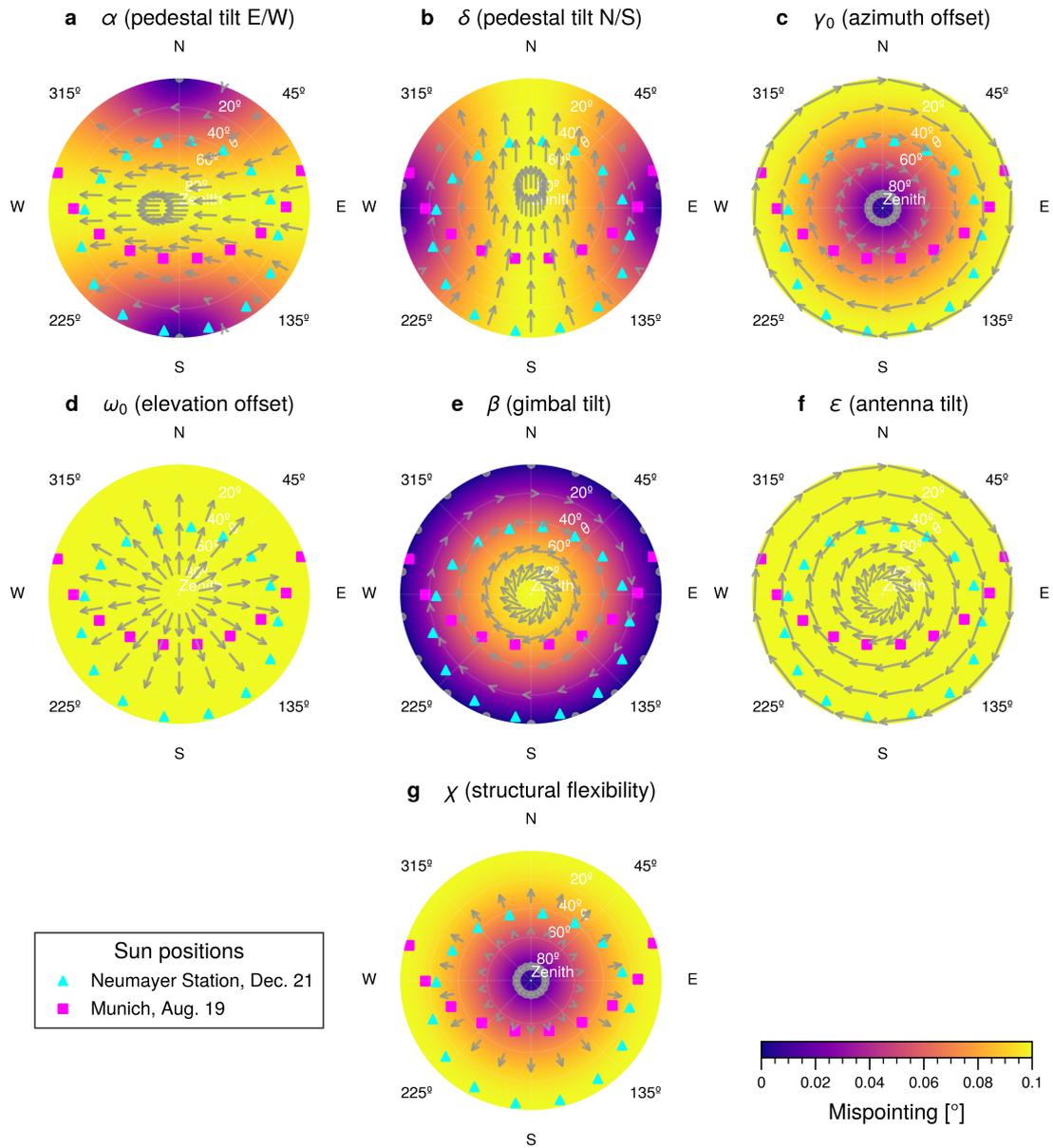
Figure 2: Same as Figure 1, but for the reverse scanner configuration. Note how the direction of the mispointing (arrows) changes for some of the parameters, compared to Figure 1.
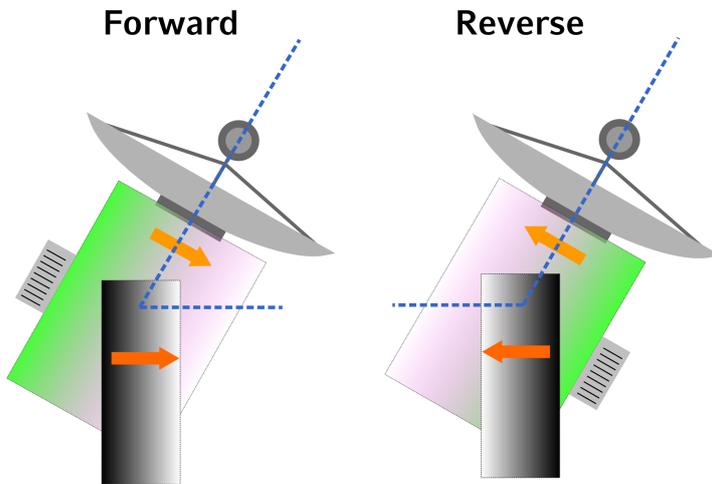
Figure 3: Illustration of the forward and reverse configuration of a two axis scanner. In both cases, the scanner points to the same location in the sky. However, in the reverse configuration, the scanner has turned by 180° in azimuth and the elevation angle (angle between the dashed, blue lines) is over 90 °. The color gradients and arrows illustrate the orientation of the pedestal and scanner box.
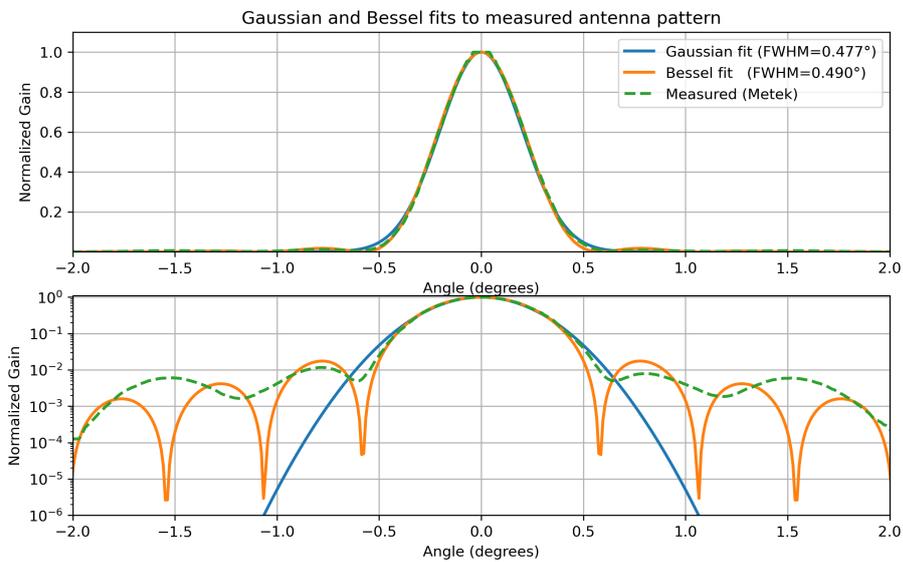

Figure 4: Comparison between a measurement of the Mira radar antenna pattern, a Gaussian pattern and a Bessel/Airy pattern. The Gaussian and Airy pattern have been fitted to the measurement using a least squares fit in linear units.