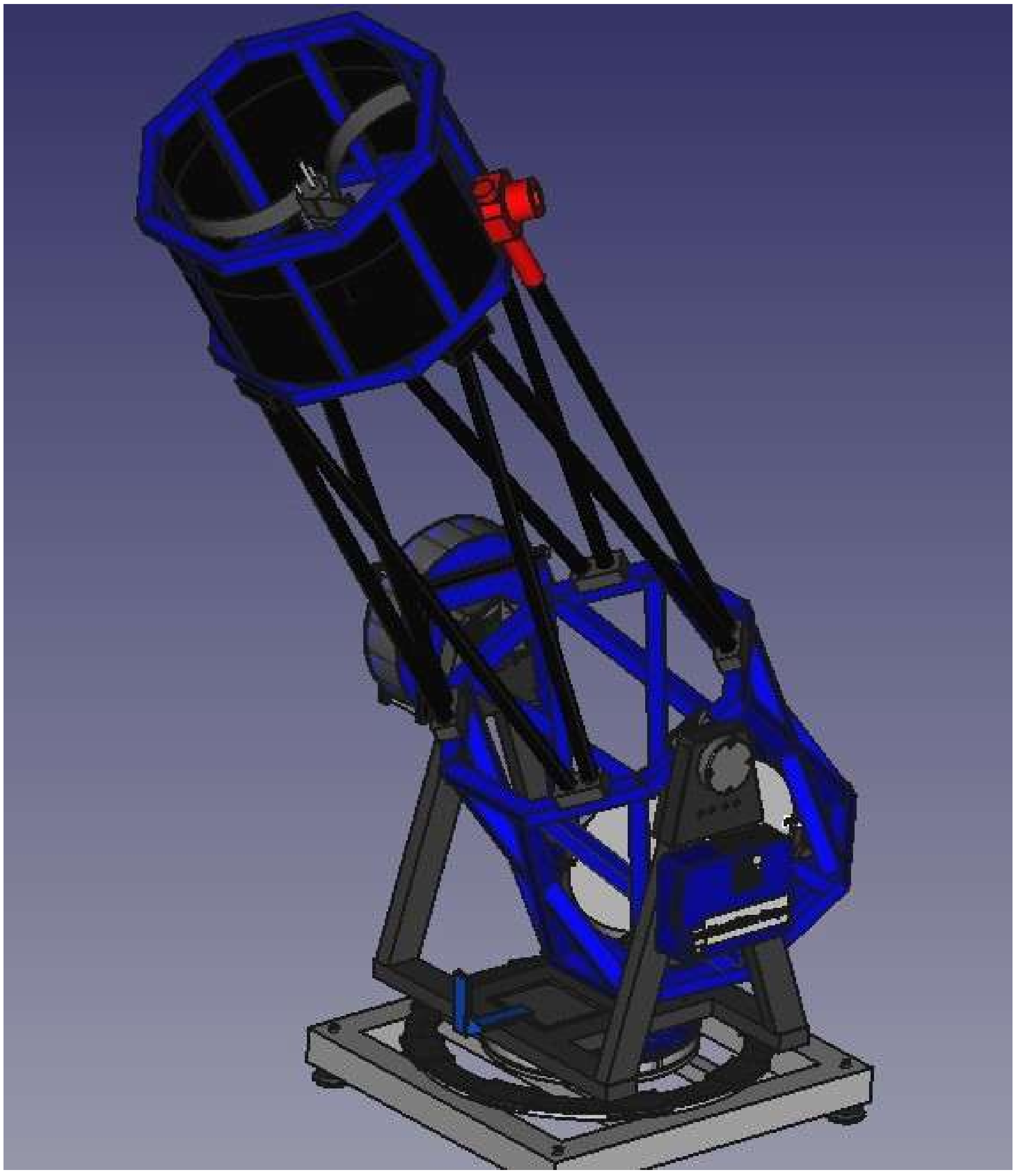
DDScopeX Motor Design Guide



Richard Benear

DDScopeX Motor Design Guide

Motors – Design Considerations

The axial-flux permanent-magnet motors described in this document are the result of an iterative design process including research, prototyping, and testing. Two prototype iterations were built before converging on the final configuration. Many academic papers address AFPM machine design; one especially useful reference was *Electromagnetic Force and Vibration Study on Axial Flux Permanent Magnet Synchronous Machines With Dual Three-Phase Windings*.

Selection of Motor Type

The telescope uses a **3-phase axial-flux permanent-magnet motor** driven from a DC power source using a motor controller (ODrive) operating in **field-oriented control (FOC)**. Compared with traditional radial-flux motors, the main advantages are:

- **Compact profile ("pancake motor")**: A flatter motor lowers the center of gravity, improving stability during tracking.
- **High torque density**: Axial-flux geometries can provide high torque for a given diameter and mass.
- **Improved cooling access**: The stator and rotor surfaces are more accessible for convection and conduction cooling.
- **Simplified construction for toothless stators**: In a toothless (air-core) stator, coils can be wound on printed bobbins without laminated iron teeth.
- **Low cogging-like effects**: Toothless stators largely eliminate traditional iron-tooth cogging. Remaining torque ripple is dominated by airgap variation, magnet nonuniformity, and winding distribution.

Design Constraints

- 3D printer bed size: Mechanical parts were constrained by a 300 mm × 300 mm print bed. This led to a motor diameter of ~280 mm to allow margin.
- Torque ("stiffness") requirements: The OTA is ~5 ft long and pivots about 25% from the base. An ALT/AZM telescope should be balanced about its altitude pivot, so steady gravitational torque is near zero; the main disturbances are wind and bumps. Because these loads were uncertain, an iterative build-test-refine approach was used.
- Pole count (magnets): Pole count influences torque smoothness and torque constant (Kt) through pole pairs, flux linkage, and winding factor. With the 280 mm diameter constraint and the use of low-cost standard N52 magnets, multiple pole counts were evaluated and 20 poles was selected.
- Number of coils: For a 3-phase machine, the number of coils must be divisible by three. Coil count affects torque ripple texture and winding distribution; it does not automatically increase torque unless effective flux linkage and winding factor improve without a large resistance penalty.
- Low-RPM operation: Telescope motors operate well below ~1 RPM, so high-speed back-EMF headroom is not a limiting factor.
- Thermal management: The design targets sufficient torque at modest current while controlling copper loss I^2R, especially because ABS bobbins have a glass transition temperature of ~105 °C.

- Ripple heuristic: For ultra-low-speed telescope drives, it is useful to think about how often the coil pattern and pole pattern “repeat” as the rotor turns. One simple way to describe this repeat behavior is the **Least Common Multiple (LCM)** between the number of coils (or slots) and the number of poles (magnets). A higher LCM generally means the geometric alignment pattern repeats less frequently, which tends to push any residual periodic torque variation to a **higher spatial frequency** (i.e., more smaller ripples per revolution).

  Important: LCM does **not** predict ripple amplitude by itself. In a toothless axial-flux motor, the dominant causes of low-speed ripple are usually:
    - air-gap variation (runout),
    - magnet strength and placement variation,
    - coil placement and winding consistency,
    - controller/current measurement noise and tuning.

  LCM is therefore best viewed as a **useful design heuristic** for the *texture* (frequency) of any repeating alignment effects, not a guarantee of smoother tracking.

  Examples:
    - LCM(15 coils, 20 poles) = 60 (this design)
    - LCM(15 coils, 18 poles) = 90 (repeat pattern is less frequent)
    - LCM(15 coils, 22 poles) = 330 (repeat pattern is much less frequent)

Final Motor Architecture

Final architecture selection is a multi-constraint optimization:

1. **Number of magnets (poles)**
   Standard N52 magnets (1.5" × 0.75" × 0.25") were mounted with the long axis radial and the 0.75" dimension tangential. The rotor diameter constraint and practical mechanical spacing led to **20 magnets (20 poles)**.
2. **Number of coils**
   With 20 poles selected, the coil count was chosen as a multiple of three. A **15-coil** stator provided a practical coil size for hand winding while maintaining good overall winding distribution and manageable resistance.
3. **Coil size tradeoff**
   Ideally, a coil’s effective active area should be on the order of the magnet face area to maximize useful flux linkage. In practice, hand winding reduces packing factor, so bobbins were intentionally oversized to make winding repeatable. This introduces copper that couples weakly to magnet flux and therefore increases I^2Rlosses without proportional torque benefit; the tradeoff was accepted for manufacturability.

Coil Design

Coils are wound on trapezoidal printed bobbins that provide mechanical clearance between coils for cooling and wiring.

Bobbins were printed in **ABS**, selected for its higher glass transition temperature (~105 °C) compared with PLA (~55 °C). Prototypes demonstrated that PLA bobbins can soften under sustained high current. Nylon was considered due to higher temperature capability but was more difficult to print reliably.

Coil Design Calculations

A conservative bobbin size was selected first to enable prototyping and to quantify resistance/heating tradeoffs.

Assumptions for the winding tradeoff table:

- The winding window is fixed by the bobbin geometry (height 18 mm; winding thickness approximately 9 mm).
- The inner turn path (used for estimating mean turn length) is approximated by a trapezoidal "racetrack" geometry with r_1 = 7.5 mm, r_2 = 2.5 mm, and center spacing d = 30 mm.
- Copper resistivity uses standard DC values at 20 °C.
- Copper heating is estimated using a balanced 3-phase RMS approximation (FOC): Pcu ≈ 3 × I_phase_rms² × R_phase

Note: Turn counts in the table assume good packing. Hand winding may reduce achievable turns/layers and should be validated experimentally.

Table A — Packing outcome vs resistance (per coil and per phase)

AWG	Turns/layer	Layers	Turns/coil	Wire length/coil (m)	Coil R (Ω)	Phase R (Ω) (5 coils series)
16	10	5	50	5.36	0.0706	0.353
18	13	7	91	10.04	0.210	1.052
19	14	7	98	10.60	0.280	1.401
20	16	8	128	13.94	0.464	2.320
21	18	9	162	17.69	0.743	3.715

Table Summary: thinner wire → more turns will fit → but wire length and resistance climb fast.

Power and Torque Notes

The N52 magnets used are a common stock size. Published magnet properties (e.g., remanence Br) provide a rough sense of available field strength, but **absolute torque prediction from geometry alone is highly uncertain** without measurement or finite element analysis. In practice, torque constant **Kt** should be measured on the assembled motor using a lever-arm test:

- Apply a known torque with a known lever arm and weight/force
- Read steady Iq
- Compute Kt = Torque / Iq

This measured Kt becomes the authoritative value for motor stiffness and thermal budgeting.

Table B — Heating and relative torque-per-amp (FOC)

Assumes "phase current" is close to **per-phase RMS** (good enough for design tradeoffs)

AWG	Phase R (Ω)	Copper loss @3.5A (W)	Copper loss @4.0A (W)	Relative torque/A *(vs 18AWG)*
16	0.353	13.0	16.9	0.55×
18	1.052	38.7	50.5	1.00×
19	1.401	51.5	67.2	1.08×
20	2.320	85.3	111.4	1.41×
21	3.715	136.5	178.3	1.78×

Table Summary:

- Going thinner than 18 AWG does buy turns (and torque/A), but heating rises sharply at 3.5–4 A.
- 20–21 AWG are not viable at 4 A unless you dramatically improve cooling or reduce current.
- 16 AWG runs cool, but you give up ~45% torque/A because you can't fit turns in the same window.
- 18–19 AWG is the "best zone" for given the current limits.

Actual measured torque for Altitude Dual Stator Motor

A 1 lbf weight was **placed** 3 ft from the **altitude axis pivot** with the OTA horizontal. The steady-state torque-producing current reported by ODrive was **Iq = 3.3 A**.

Torque constant from measured Iq

Kt (N·m/A) = T (N·m) / Iq (A)

Expected torque at current limit (using measured Kt)

Using Kt = 1.232 N·m/A, the expected torque is:

- At Iq = 3.5 A: T = 1.232 × 3.5 = 4.31 N·m
- At Iq = 4.0 A: T = 1.232 × 4.0 = 4.93 N·m

Note: Use the steady-state Iq value after the axis settles; transient peaks include inertia and controller dynamics.

Measured example (1 lbf at 3 ft, Iq = 3.3 A)

- Imperial torque: T = 1 × 3 = 3 ft·lbf
- Metric torque: T = 3 × 1.35581795 = 4.067 N·m
- Torque constant: Kt = 4.067 / 3.3 = 1.232 N·m/A

Equivalent tangential force at motor radius (r = 95 mm)

This torque corresponds to a tangential force at r = 0.095 m of:

- F = T / r = 4.067 / 0.095 = 42.8 N
- F = 42.8 / 4.448 = 9.6 lbf

Table C — Power with stators in parallel (Altitude motor)

The altitude axis uses two identical stators arranged as a sandwich around the rotor, wired electrically in parallel.

For two identical stators in parallel:

- The effective phase resistance is approximately **halved**.

- For the **same total torque**, copper loss is reduced because current divides between stators.
- Torque only doubles if the total torque-producing current (Iq) delivered to the motor doubles.

AWG	Phase R (dual stators parallel) (Ω)	Copper loss @4.0A (W)
16	0.176	8.47
18	0.526	25.25
19	0.700	33.62
20	1.160	55.68
21	1.857	89.15

Operating Limits

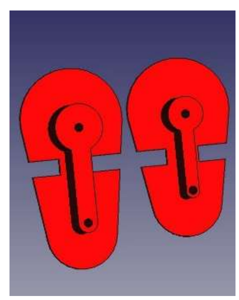
The final DDScopeX design uses 18 AWG windings. Using the winding-model estimate, this corresponds to ~50 W copper loss at 4 A (single-stator case). This level of dissipation cannot be sustained indefinitely without forced cooling, so firmware safeguards are required. DDScopeX limits motor operation by shutting down if current exceeds ~4 A for more than ~5 seconds.

Future Architecture

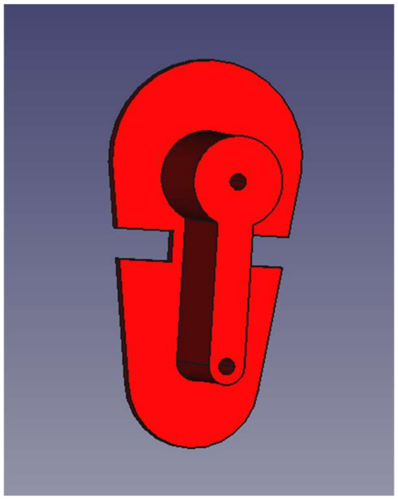
Based on build experience and analysis, an optimized coil would be **shorter radially** and **slightly narrower tangentially** while maintaining 91 turns. This reduces "weak-flux copper," improves torque-per-watt, and lowers coil temperature rise. Achieving the same turns in a smaller bobbin requires improved packing factor (more uniform winding) or mechanical changes that increase the winding window.

Candidate optimized coil dimensions (trapezoidal outer):

- Radial length (long axis): **56 mm** (down from 63 mm)
- Top width: **30 mm** (down from 32 mm)
- Bottom width: **21 mm** (down from 22 mm)
- Mounting holes: 6 mm closer (21.4 mm instead of 27.4 mm)

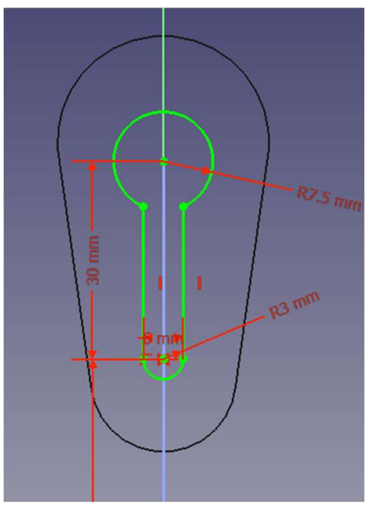


Original coil bobbin on left, small optimized on right

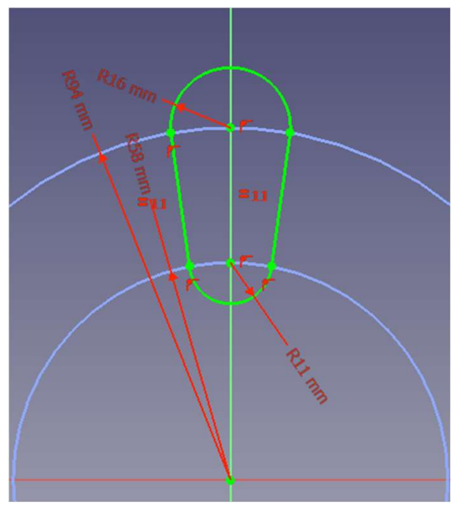


Original 3D Printed Coil Bobbin (ABS Plastic)

- Notches are for access ports for tie wraps
- Tie wraps around wires holds wires together (not shown)
- Top holes were intended to add a top but this was not used so the gap could be smaller between coils and magnets.
- Holes on bottom are used to mount to stator plate.



Bobbin dimensions (any new design should use shorter length for optimum flux coupling)



Top of bobbin. This was not used.

Motor Construction

Altitude Motor

The Altitude motor is a Dual Stator Single Rotor Axial Flux Permanent Magnet 3-phase design. Effectively, this is 2 motors in a compact package and produces twice the torque which is needed to counter the rotation inertia of the OTA.

Two-Sided Rotor Design

The base plate of the rotor is ¼" (0.25" or 6.35 mm) thick steel plate that was plasma cut into a 250 mm diameter circle where the steel was purchased. Other holes were drilled in my workshop. Earlier versions of the rotor used 16-gauge (0.06" or 1.52 mm) steel. This was found to be too flexible because, when the motor was operating, the strong magnetic fields would flex the steel and couple the physical movement into the encoder causing positive feedback in the servo controller and severe vibration.

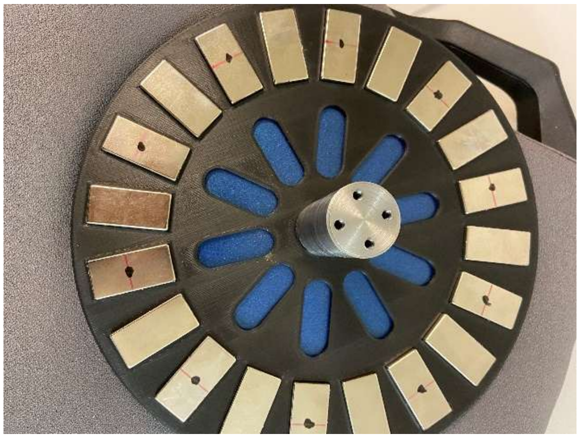
There are 20 magnets on each side of the rotor for a total of 40 magnets. To help position the magnets evenly, a 3D printed alignment mask was made. Magnets were placed in the slots and glued with cyanoacrylate glue (superglue) to the steel. A dab of silicon may also work and was used to hold the mask to the rotor steel plate. Care must be taken to alternate the north and south poles around the perimeter. Marking them with a dot will help even though the magnets came with a faint red line marking the polarity.

Since there are magnets on both sides of the rotor plate because this is a double motor, there are two masks: one on both sides. Masks should be exactly aligned so that magnets are directly across from each other. Since the magnets are directly across the rotor plate from each other, then the poles will need to be opposite each other since it would nearly be impossible for the same poles to be across from each other since they would repel.

Important!! Caution should be used when putting these magnets onto the steel plate. They are very strong and will jump out of your hands and shatter, break, or pinch your fingers.

There is a 30 mm diameter axle welded to the ¼" thick steel rotor plate in the center. Holes are drilled and tapped in the other end of the axle. The rotor axle will go through the inside stator bearing and another bearing in the top of the fork mount. The axle must be welded as perpendicular as possible to the rotor or there will be a wobble in the rotor.

The outside part of the rotor plate has holes drilled and tapped to hold a 3D printed hub that holds a bearing for the outside stator and has a cylindrical protrusion where the rotating part of the encoder will connect.



Altitude Motor Rotor

- Note that a 3D printed magnet placement mask was used for accuracy. Oval gaps are meant to reduce the amount of filament that was used.
- Dots on magnets represent they are South poles up. Others are North poles up.
- Axle is welded to metal rotor plate exactly perpendicular to plate.
- The other side of rotor has the same mask and magnet arrangement except the polarity of the magnets that are face-to-face are opposite.

Altitude Motor Assembly

- Shown partially assembled.
- Inside stator is shown with the rotor and outer bearing.
- Outside stator is not shown.

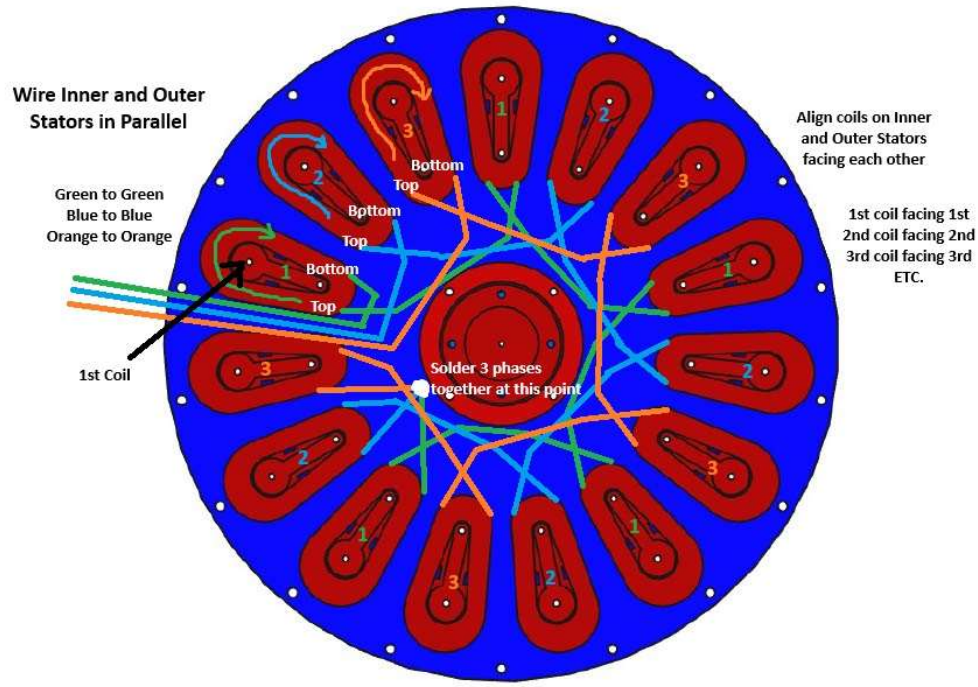
Dual Stator Design

As stated previously, the Altitude (ALT) motor has 2 Stators which effectively create a double motor. The stators use a 14-gauge (1.9 mm) steel plate which is 172 mm in diameter. The Inner and Outer Stators have 15 coils each. The Azimuth Stator has 15 coils. All coils have 91 turns consisting of 13 wires per layer and 7 layers. Cable ties are used to hold the wires in place. The coils are mounted on a 3D printed coil holder using either silicon or another adhesive such as cyanoacrylate (superglue). There is a slot in the bottom portion of the coil holder to allow room for the cable tie. Similarly, there is a slot in the coil form used by the coil winding machine to allow putting the cable ties on before removing them from the coil winder. The orientation is the same for all coils. The coil holder is then screwed to the Stator backing plate.

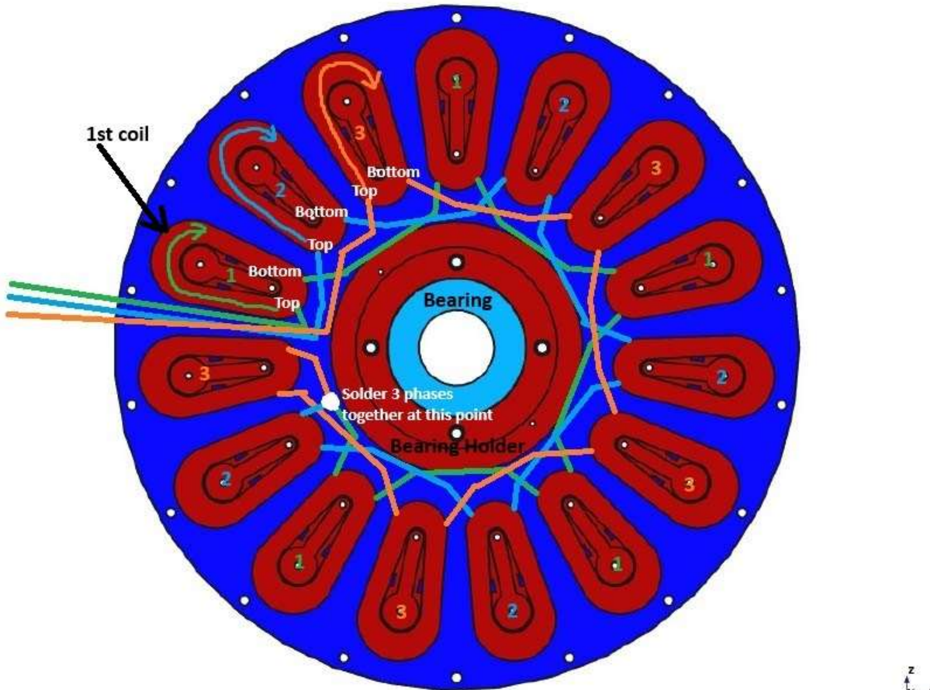
Originally, the plan was to have a 3D printed top for the coil holder that would provide protection from the rotor but this was eliminated so that the space between the coil and magnets could be another millimeter closer to get more torque because of increased magnetic field coupling. But it is *important* to make sure the coils do not rub on the magnets when the rotor is rotating which may rub off the insulation of the wires thus shorting them together.

The wiring of the stator coils is shown in the drawings below. The Outer Stator coils are wired so that their magnetic field is opposite of the Inner Stator coils. Since all coils on the Inner or Outer Stator are mounted in the same orientation, that means that it is important to connect the Top and Bottom coil wires as indicated in the drawings below so that the magnetic fields are going in the right direction. This is because the magnets on the rotor have opposite polarity on the side facing the respective stator. The 1st coil in the phase of the Inner and Outer stator is aligned opposite or facing each other. Solder the wires together for their respective phases as indicated in the diagram and put shrink tubing around the joints.

The 3-phase wiring between the Inner and Outer Stators is a parallel wiring arrangement. Each phase of the Inner and Outer Stator should separately be connected (soldered) together.



ALT Motor Outer Stator Wiring



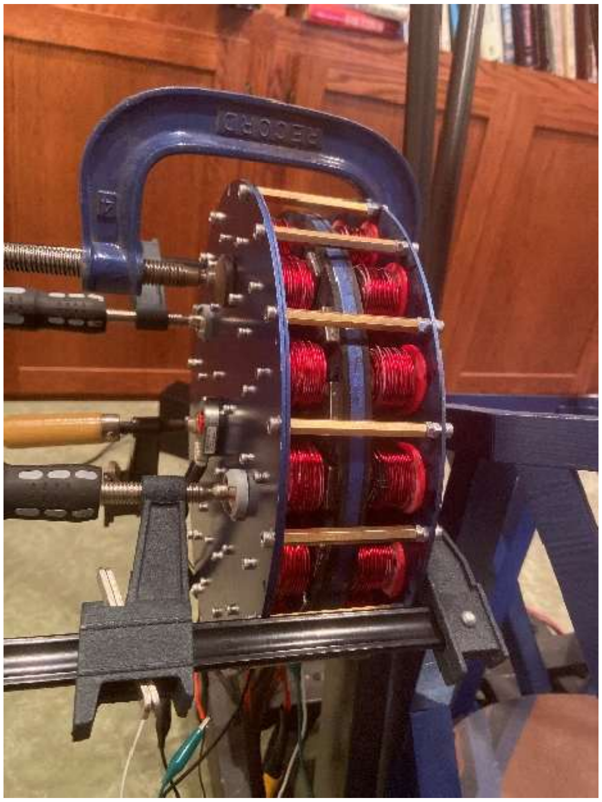
ALT Motor Inner Stator Wiring

Inner stator of Dual Altitude Motor

Outer stator of Dual Altitude Motor

Assembly of the two Stators halves with the Rotor is accomplished using a series of 16 standoffs on the outer periphery of the motor. These standoffs were 60 mm in length but washers were added on each end of the standoffs to “tune” the gap between the rotor and stators to be as small as possible without any rubbing. The Encoder was mounted on the outside of the Outer Stator.

Once assembled, the motor was driven with the ODrive Motor Controller in a tuning configuration so that the best loop gains could be determined. It quickly became evident that once the gains were increased that a self-resonance or oscillation occurred. This was determined to be due to the strong oscillating magnetic fields flexing the steel Stator mounting plates and coupling that movement into the Encoder thus providing a positive feedback oscillation. In the pictures below, there was some experimentation with C-clamps to find the best places to dampen the vibration. A steel frame was welded out of ½” steel tubing and clamped around the Altitude motor. This effectively solved the problem. Another solution would probably be to make the stator mounting plates out of thicker steel and/or with steel flanges.



Altitude Motor Assembly – clamps are to figure out where are the unwanted vibrations

Altitude Motor with vibration damping steel frame

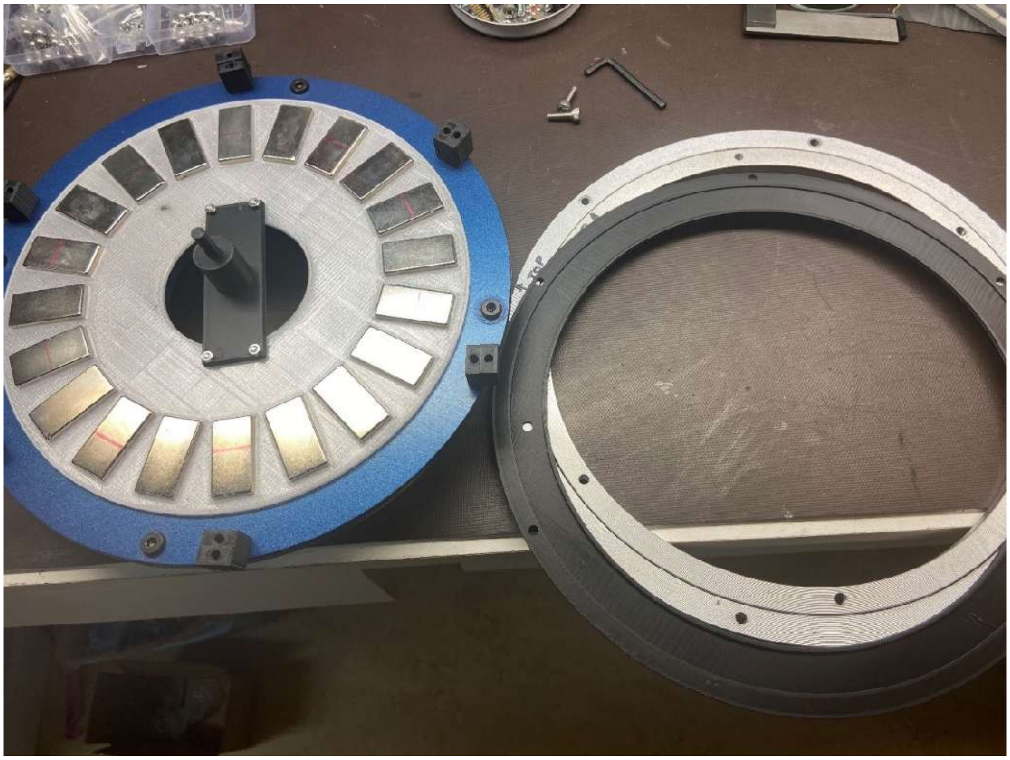
Azimuth Motor Construction

The Azimuth Motor is a single Stator and Rotor design. After design iterations using a 6006-2RS (55 mm diameter) ball bearing with an axle in the center as was used in the Altitude Motor, it was decided that the best way to bring cables for the encoder out from the motor was to go through the middle of the motor and use a slew bearing. The slew bearing is a 12” (300 mm) diameter bearing intended to be used as a “Lazy Susan” and was purchased from Amazon. This change in design meant that the encoder cable did not have to move as far thus risking pinching and crimping of the cable. The encoder cable could also be shorter thus less susceptible to noise. The slew bearing fits around the periphery of the motor with the added benefit of providing much improved axial stability.

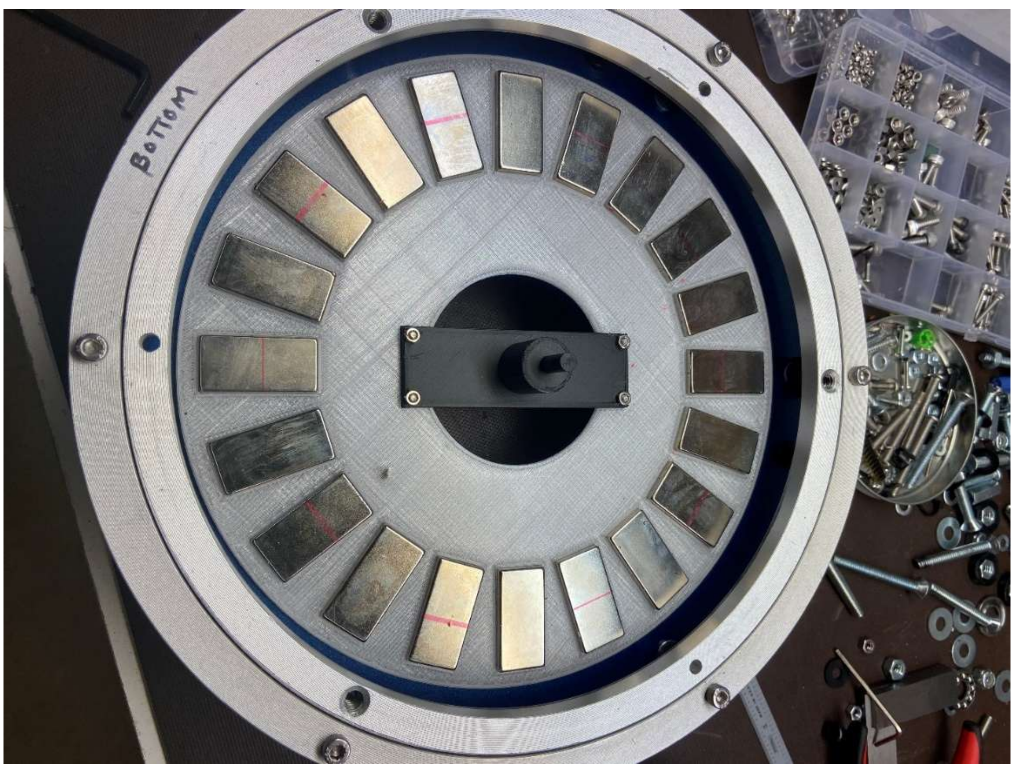
Rotor

The Azimuth Rotor has 20 magnets on one side of the ¼” thick x 11.26” (6.35 mm x 286 mm) diameter steel plate. A 3D printed template helps orient the magnets in the correct positions and to keep them in place. The polarity of the magnets alternates from North to South as they go around the periphery of the rotor. The magnets and template are glued to the steel rotor plate using either silicon or superglue.

Plastic standoffs are 3D printed to keep the spacing between the rotor and stator consistent. The standoffs connect the rotor steel plate to the outer ring of the slew bearing. The stator will connect to the inner ring of the slew bearing.



Azimuth Motor Rotor Assembly – Slew Bearing and bearing dust shield on the right



Azimuth Motor Assembly – rotor is attached to the outside ring of the slew bearing.
The telescope forks mount to the rotor (backside of this view).

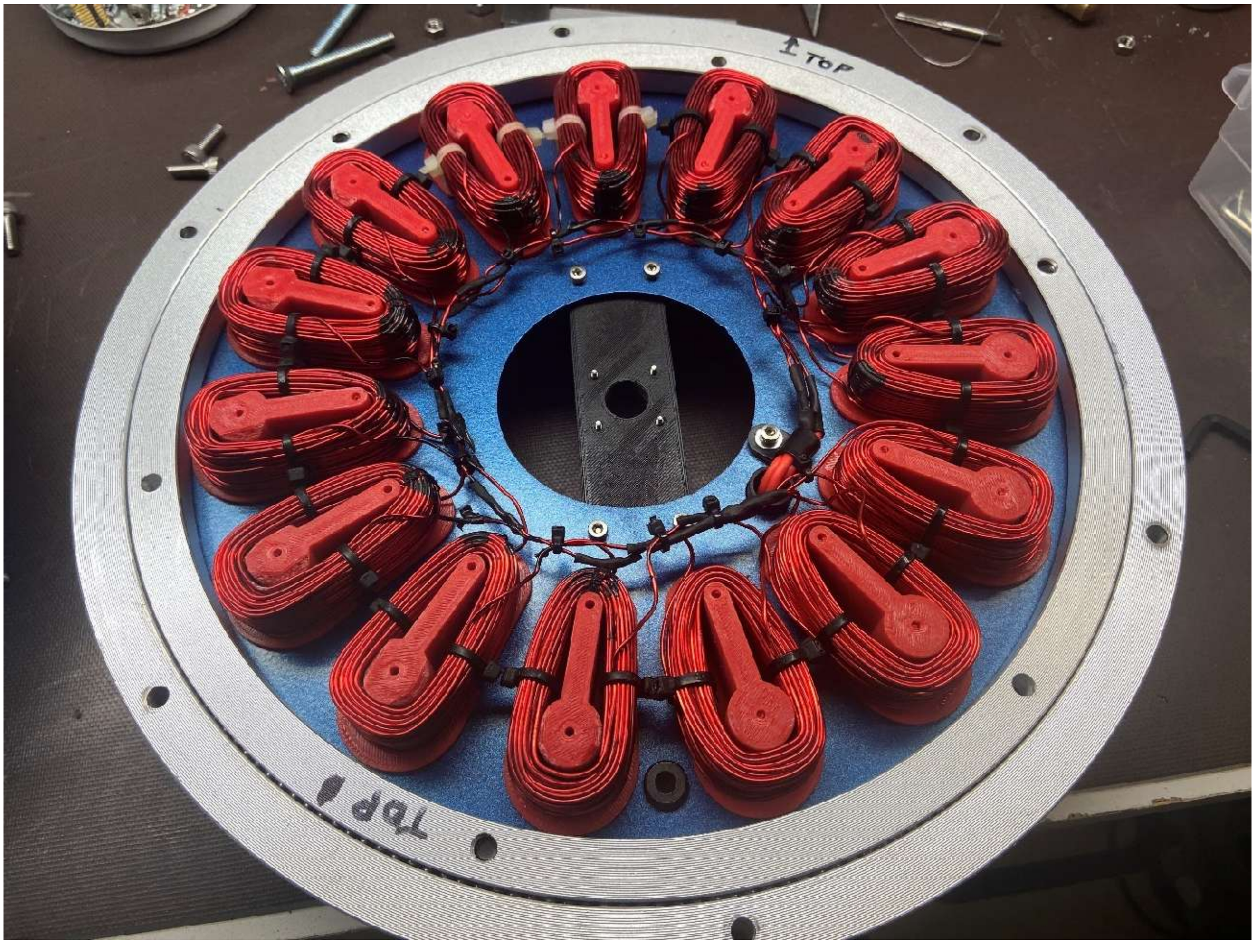
The 3D printed encoder axle is attached in the center.

Stator

The Azimuth Motor Stator is constructed with a 11 gauge (3.0 mm) thick steel plate and is 10.7” (272 mm) in diameter. The Azimuth Stator has 15 coils mounted on this steel plate. All coils have 91 turns consisting of 9 wires per layer and 17 layers. Cable ties are used to hold the wires in place. The coils are mounted on a 3D printed coil holder using either silicon or another adhesive such as cyanoacrylate (superglue). There is a slot in the bottom portion of the coil holder to allow room for the cable tie. Similarly, there is a slot in the coil form used by the coil winding machine to allow putting the cable ties on before removing them from the coil winder. Enough adhesive should be used to keep wires from moving and rubbing together. The orientation is the same for all coils. This holder is then screwed to the Stator backing plate.

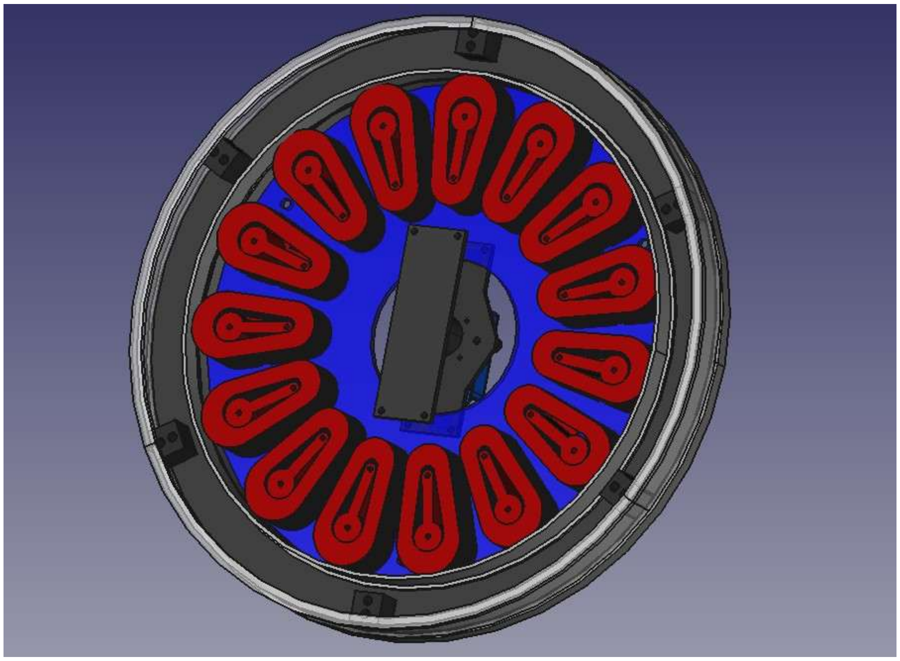
Wiring the coils for each phase together is the same as with the Altitude Motor Inner Stator (refer to the diagram in that section). Solder the wires and put shrink tubing around the joints. The 3 wires for phase connections are fed through a hole in the stator plate. A clamp around the wires is added to minimize any unwanted movement.

Originally, the plan was to have a 3D printed top for the coil holder that would provide protection for the coil wires from the rotor but this was eliminated so that the space between the coil and magnets could be another millimeter closer resulting in more torque. But it is *important* to make sure the coils do not rub on the magnets when the rotor is rotating.

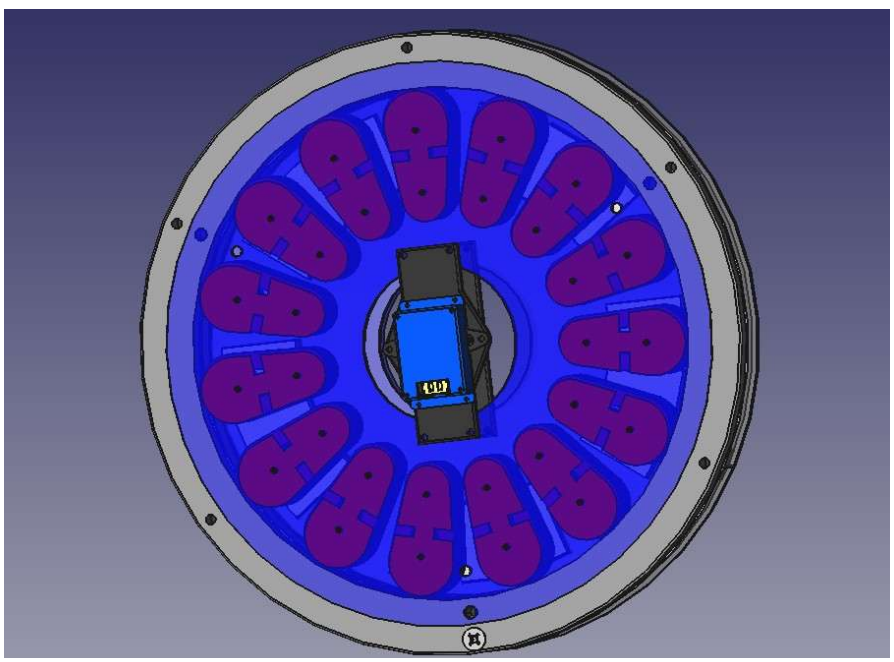


Other AZM Motor components

The completed motor with the Rotor removed viewed from the Top. Note that there are 6 standoffs that were 3D printed to attach the Rotor to the Stator. Shown in the center is the 3D printed Encoder axle. It is the rectangular object and is screwed to the Rotor with 4 screws on the bottom side of the rotor.



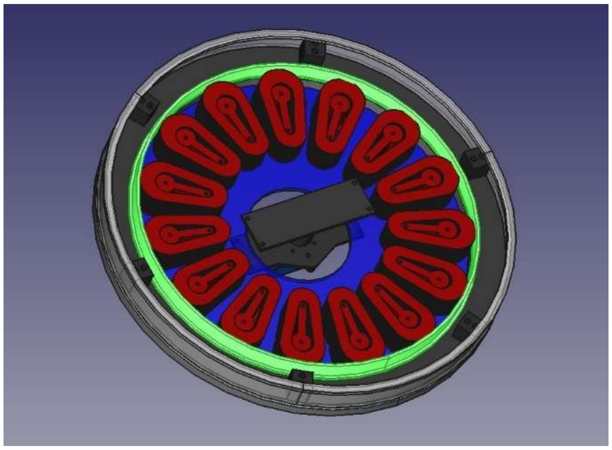
The bottom view of the AZM Motor with the Stator steel plate shown with some transparency so that internal placements of the components are visible. There is an Encoder mounting plate (3D printed) that screws to the bottom of the Stator steel plate. The Encoder mount housing which comes with the encoder is screwed to the mounting plate. A 3D printed Encoder dust cover in shown also (in blue).



The Top view of the AZM motor is shown below with the Rotor steel plate in a semi-transparent mode so that the internal components are somewhat visible. The magnets and the magnet alignment template are shown.

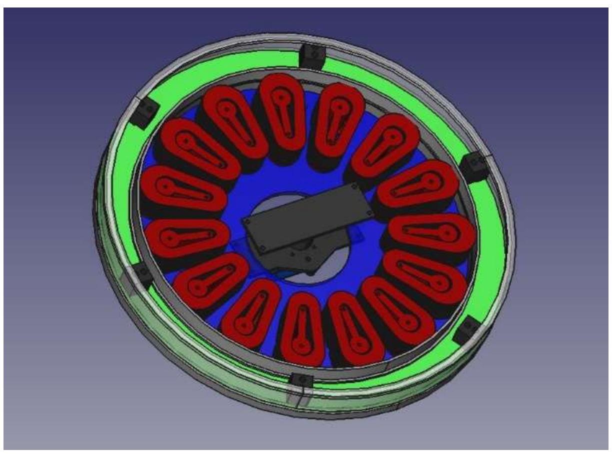
Shields

There are 3 dust shields to keep unwanted debris out of the motor. These were created on the 3D printer. The green sections in the pictures below are the shields.



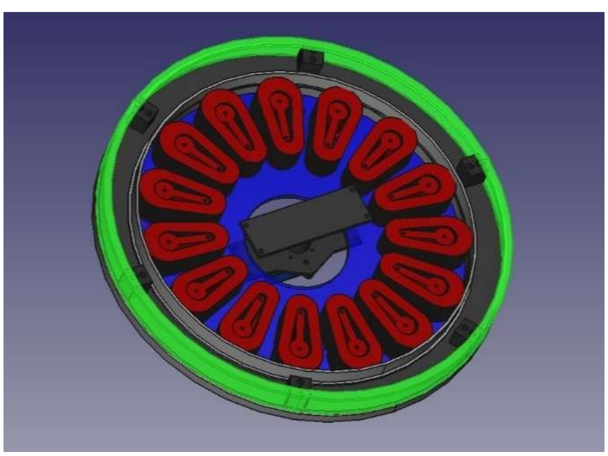
Rotor Magnet Dust Shield

The magnets would attract metal particles eventually causing problems so there is Magnet Dust Shield.



Slew Bearing Shield

This dust shield for the slew bearing will keep particles out of the bearing grooves.



Motor Dust Shield

This dust shield surrounds the complete motor. It was 3D printed in 6 segments and each segment was screwed into the standoffs since the 3D printer could not handle the full diameter.