Carousel mechanism design

Project: *LuSEE-Night*
System: *Antenna Carousel*
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Abstract: Assessment of carousel (a.k.a. "turntable") mechanism and torques for the LuSEE-Night lunar instrument. The radio antennas rotate on a platform. Key design parameters and options for the rotation mechanism are considered here.

Preliminaries

Units and coordinate systems

Except where otherwise specified...

- all units are in meters, kilograms, newtons, and seconds
- all inertias and positions are with respect to a global coordinate system, with Z axis concentric to rotation axis

Python initializations and units

In [1]:
```
import math
deg = '\u00b0'
tab = f'{" ":4}'
horiz_rule = ''.join(['-']*10)
Nm_per_ozin = 1 / 141.61193227806
m_per_in = 0.0254
radpersec_per_rpm = 2 * math.pi / 60  # i.e. rad/sec per rev/min
K_to_other = {'K': lambda T: T,
              'C': lambda T: T - 273.15,
              'F': lambda T: (T - 273.15)*9/5 + 32.0,
             }
```

General material properties

In [2]:
```
rho_SS = 8000  # stainless steel density
rho_Ti = 4430  # titanium density
rho_Al = 2700  # aluminum density
rho_BeCu = 8300  # beryllium copper density
rho_Cu = 8900  # copper density
rho_plastic = 1300  # generic plastic density
E_Cu = 117e9 # copper modulus of elasticity
E_plastic = 2e9 # generic plastic modulus of elasticity
```

```
E_BeCu = 130e9  # beryllium copper modulus of elasticity
nu_BeCu = 0.3  # beryllium copper poisson ratio
```

Carbon fiber properties

In [3]:
```
rho_f = 2170  # carbon fiber density, e.g. CN-80
rho_m = 1170  # resin matrix density, e.g. EX-1515
Mm = 0.32  # matrix mass fraction, i.e. prepreg resin content from vendor
Vv = 0.005  # as-cured void fraction
Vf = (1 - Vv) / (1 + rho_f / rho_m * Mm / (1 - Mm))  # fiber volume fraction, assuming
cfrp_density = rho_f * Vf + rho_m * (1 - Vf - Vv)
print(f'Estimated carbon fiber reinforced plastic (CFRP) density = {cfrp_density:.1f}
```

```
Estimated carbon fiber reinforced plastic (CFRP) density = 1695.4 kg/m^3, volume frac
tion = 53.1%
```

Other basic system properties

In [4]:
```
n_ant = 4  # number of antennas
operating_range_deg = 180  # degrees, within which the turntable needs to be able to p
rotation_range_margin_deg = 5  # degrees, extra mechanical positioning range for antib
rotation_range_margin = math.radians(rotation_range_margin_deg)
rotation_range = [math.radians(operating_range_deg)/2 + rotation_range_margin,
                  -math.radians(operating_range_deg)/2 - rotation_range_margin]  # radi
total_rotation_range = max(rotation_range) - min(rotation_range)
print(f'Total rotation range = {total_rotation_range:.3f} rad = {math.degrees(total_ro
```

```
Total rotation range = 3.316 rad = 190.0 deg
```

Key mechanical design criteria

The design criteria below will be used in sizing components and ensuring sufficient mechanical factors of safey. These criteria are informed by key recommendations in NASA's General Environmental Verification Standards (GEVS) (accessed 2022-07-09).

Structural load limit

The limit loads for the carousel mechanism are derived from GEVS Table 2.4-3, *Generalized Random Vibration Test Levels*. For components weighing less than 22.7 kg, an overall qualification level (in G_{rms}) is directly specified. We then apply a proof factor per section 2.4.1.4.1, and a design factor to get the design limit. The design factor accommodated uncertainty in material properties and tolerances in the proof test method. These limits are applied for nominal accelerations in 3 orthogonal axes.

In [5]:
```
Grms_qual = 14.1
proof_factor = 1.25
design_factor = 1.2
Grms_design = Grms_qual * proof_factor * design_factor
print(f'Design load level = {Grms_design:.1f} G(rms)')
```

```
Design load level = 21.1 G(rms)
```

Torque margin

Torque margin (TM) for the carousel turntable is assessed per GEVS section 2.4.5.3. Two safety factors, FS_k and FS_v are applied to the "known" and "variable" torques in the system. GEVS states:

> The minimum available driving torque for the mechanism shall be determined based on the FS listed above. The Torque Margin (TM) shall be greater than zero and shall be calculated using the following formula:
>
> $$TM = \frac{T_{avail}}{FS_k \sum T_{known} + FS_v \sum T_{variable}} - 1$$

In the present study, the available driving torque T_{avail} is considered at output of the the gearmotor (which is the component whose performance requirements we are aiming to specify). The torques are defined in GEVS as:

> **Driving Torques**
>
> T_{avail} = Minimum Available Torque or Force generated by the mechanism at worst case environmental conditions at any time in its life. If motors are used in the system, T_{avail} shall be determined at the output of the motor, not including gear heads or gear trains at its output based on minimum supplied motor voltage. T_{avail} similarly applies to other actuators such as springs, pyrotechnics, solenoids, heat actuated devices, etc.
>
> **Resistive Torques**
>
> $\sum T_{known}$ = Sum of the fixed torques or forces that are known and quantifiable such as accelerated inertias ($T = I\alpha$) and not influenced by friction, temperature, life, etc. A constant Safety Factor is applied to the calculated torque.
>
> $\sum T_{variable}$ = Sum of the torques or forces that may vary over environmental conditions and life such as static or dynamic friction, alignment effects, latching forces, wire harness loads, damper drag, variations in lubricant effectiveness, including degradation or depletion of lubricant over life, etc.

Here we use the highest (PDR phase) torque safety factor values from GEVS:

In [6]:
```
FSk = 2.0  # 2.0 at preliminary design review phase
           # drops to 1.5 at critical design review
           # remains 1.5 at acceptance / qualification testing

FSv = 4.0  # 4.0 at preliminary design review phase
           # drops to 3.0 at critical design review
           # drops to 2.0 at acceptance / qualification testing
```

Thermal criteria

The carousel system must survive the lunar day/night cycle. It must operate at intermediate temperatures around dusk/dawn.

The plots below, showing lunar temperature as a function of hour and latitude, were retrieved July 2022 from an article (exact reference?) found through citations here:

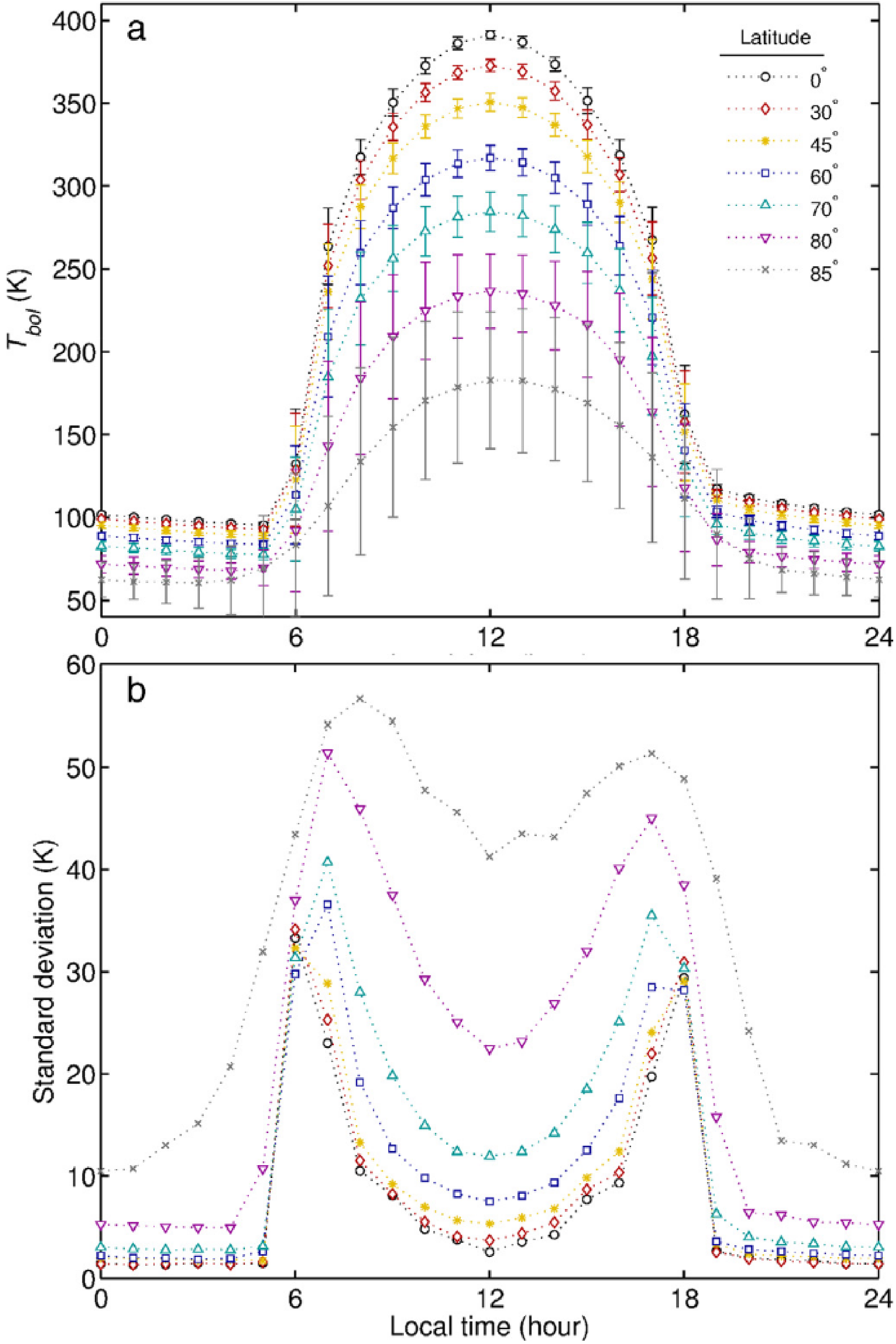


Fig. 9. (a) Zonal mean bolometric temperatures and (b) standard deviation versus local time for latitude bands 0°, 30°, 45° 60°, 70°, 80°, and 85°.

We anticipate LuSEE-Night will land at one of two sites:

1. 155^o E and 15^o S
2. 175^o E and 22^o S

These indicate that the lander will experience temperature extrema of:

In [7]:
```
temp_ranges = {'extrema': [90, 390]}  # Kelvin
```

Survival temperature range

For design and testing purposes, the survival temperature range is obtained by increasing the expected lunar range by a margin on either end.

In [8]:
```
temp_margin = 10.0  # deg C
temp_ranges['survival'] = [min(temp_ranges['extrema']) - temp_margin,
                           max(temp_ranges['extrema']) + temp_margin]
```

Operating temperature range

The operating temperature for carousel rotation will be less extreme. We want a range which is moderate enough to includes practical motors, transmissions, and bearings, yet wide enough to allow a significant period in the dusk/dawn time window where ground-based operators can effectively send commands, monitor the response, and make any adjustments if necessary. A good operating temperature range also offers practical conditions for testing in the lab.

? Under the assumption of a perfluoropolyether (PFPE) based lubricant in the gears and bearings ... ?

? For what temperature range do we have equipment on hand to practically test operation of the motors, bearings, transmissions---the full turntable assembly---in vacuum ?

Considering these factors, we propose an operating temperature range of 280 K - 320 K, which should provide generous time windows ($\sim$ 1 lunar hour $\approx$ 30 earth hours each), at lunar dawn and dusk.

In [9]:
```
temp_ranges['operating'] = [280, 320]
```

Temperature ranges summary

In [10]:
```
for name, temp_range in temp_ranges.items():
    for unit, func in K_to_other.items():
        converted = [func(T) for T in temp_range]
        print(f'Temperature range = {min(converted):+4.0f} to {max(converted):+4.0f} {
    print('')
```

```
Temperature range =  +90 to +390 °K (extrema)
Temperature range = -183 to +117 °C (extrema)
Temperature range = -298 to +242 °F (extrema)

Temperature range =  +80 to +400 °K (survival)
Temperature range = -193 to +127 °C (survival)
Temperature range = -316 to +260 °F (survival)

Temperature range = +280 to +320 °K (operating)
Temperature range =   +7 to  +47 °C (operating)
Temperature range =  +44 to +116 °F (operating)
```

Loads

Total mass budget for the carousel system is:

In [11]:
```
mass_budget_total = 7.8  # kg
```

Some fraction of this mass (in particular the drive motor and transmission) will be static.

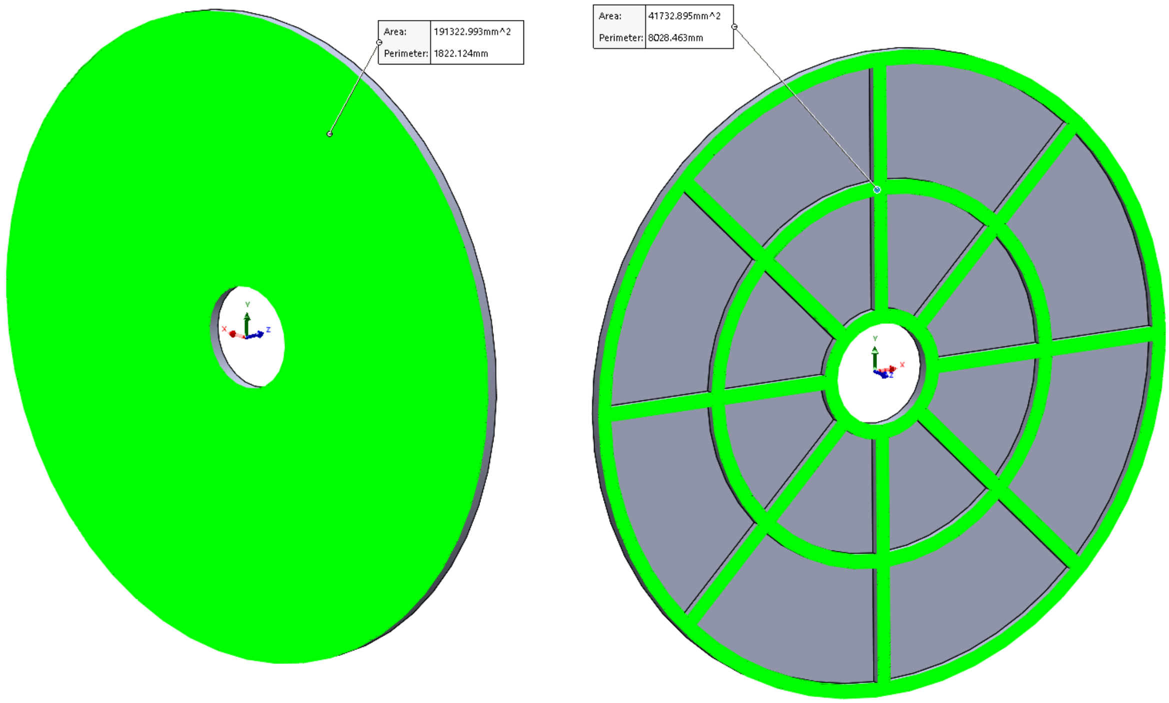
For the purposes of this document, we subdivide the rotating payload into the following estimated masses, moments, and transmission ratios.

Turntable plate

Three common engineering materials are being considered for the turntable platter: aluminum, titanium, or carbon fiber reinforced plastic (CFRP).

In [12]:
```
plate_od = 0.500  # outer diameter
plate_id = 0.079  # inner diameter
plate_t = 0.010  # thickness
plate_r2, plate_r1 = plate_od/2, plate_id/2  # radii
plate_area = math.pi * (plate_r2**2 - plate_r1**2)
uniform_plate_inertia_over_mass = 0.5 * (plate_r1**2 + plate_r2**2)
```

Bending stiffness is achieved either through a honeycomb core or ribs (of which a nominal design might look like that illustrated here:



In [13]:
```
core_vf = 0.15 # honeycomb core volume fraction, typically about 8-32% depending on de
ribs_af = 0.20 # approx area fraction of some nominal ribs stiffening design for turnt
```

CFRP sandwich construction

CFRP would have a higher stiffness per unit mass than the metals, as well as some natural structural damping. We would likely use an intermediate modulus fiber in a quasi-isotropic, balanced, symmetric layup. Matrix would be 350^{o}F (450 K) cured resin such as Toray RS-3C, commonly used in spacecraft. The design would need to be sufficiently low-strain such that the total temperature change from processing (450 K) down to lunar night (100 K) does not exceed fiber strain limits. A honeycomb sandwich construction would be most mass-efficient, with titanium or aluminum inserts at bolted connections. Thermal expansion effects would be low, several parts per million (ppm) per degree K. Low out-of-plane thermal conductivity would be of some benefit in reducing the heat transfer rate from the turntable to the rest of the spacecraft below it. The main detractions of CFRP are the higher design and fabrication costs.

In [14]:
```
plate_sandwich_skin_t = 0.0016
plate_sandwich_core_t = plate_t - 2 * plate_sandwich_skin_t
plate_sandwich_skin_rho = cfrp_density
plate_sandwich_core_rho = rho_Al * core_vf
plate_sandwich_mass = (2*plate_sandwich_skin_rho*plate_sandwich_skin_t + plate_sandwic
plate_masses = {'CFRP sandwich': plate_sandwich_mass}
```

Metal ribbed plate construction

Material would be either titanium or aluminum.

A machined aluminum plate would be the least expensive to fabricate. Detractions are the higher CTE (∼12-25 ppm/K over the 100K-400K temperature range) and reduced stress allowables at sustained high temperature (7075-T651 aluminum, for example, may have yield strength reduction from $\sim$ 500 MPa at room temperature to $\sim$ 180 MPa when sustained at 150^o C (423 K). The high thermal conductivity of aluminum allows faster heat transfer toward the spacecraft. All these detractions can likely be mitigated with use of appropriate design allowables and thermal breaks.

Grade 5 titanium would be a robust solution. Material cost would be comparable to CFRP, though fabrication complexity would be simpler. CTE is relatively low and stable ($\sim$5-9 ppm/K over range 100K-400K), strength is high, and the very low thermal conductivity ($\sim$5-8 W/m*K) would provide some natural insulation of the rest of the spacecraft from the exposed turntable's temperature. For cost and ease of manufacturing we would probably not machine the plate out of thick titanium, but rather screw together a thinner face sheet with stiffening ribs.

In [15]:
```
plate_rhos = {'aluminum': rho_Al,
              'titanium': rho_Ti,
             }  # density
plate_face_t = 0.0016  # face plate thickness
plate_ribs_t = plate_t - plate_face_t
plate_volume = (plate_face_t + plate_ribs_t * ribs_af) * plate_area
for name, rho in plate_rhos.items():
    plate_masses[name] = rho * plate_volume
```

Plate construction options summary

In [16]:
```
plate_inertias = {}
for name, mass in plate_masses.items():
    plate_inertias[name] = mass * uniform_plate_inertia_over_mass  # note this uniforn
    print(f'Turntable mass = {plate_masses[name]:.3f} kg, inertia = {plate_inertias[na
```

```
Turntable mass = 1.566 kg, inertia = 0.0502 kg/m^2 (CFRP sandwich)
Turntable mass = 1.695 kg, inertia = 0.0543 kg/m^2 (aluminum)
Turntable mass = 2.782 kg, inertia = 0.0891 kg/m^2 (titanium)
```

In [17]:
```
# For purposes of motor sizing, select the heaviest option.
plate_mass = max(plate_masses.values())
plate_inertia = max(plate_inertias.values())
```

Antennas

The four antennas will be stacer tubes, equally spaced around the turntable. Deployed length is 3 m for all antennas. Deployment angle is slightly above horizontal, counteracting gravity sag. Here this slight bend is neglected, and treated as purely horizontal.

In [18]:
```
boom_deployed_wall_in = 0.005  # inches, antenna approx wall thickness when deployed
boom_deployed_diam_in = 0.35  # inches, antenna approx diameter when deployed
boom_wall, boom_diam, boom_area, boom_length, boom_inertia = {}, {}, {}, {}, {}
boom_wall['deployed'] = boom_deployed_wall_in * m_per_in
boom_diam['deployed'] = boom_deployed_diam_in * m_per_in
boom_area['deployed'] = math.pi * boom_diam['deployed'] * boom_wall['deployed']
boom_length['deployed'] = 3.0
boom_volume = boom_length['deployed'] * boom_area['deployed']
boom_rho = rho_BeCu  # select material for antenna
```

```
boom_mass = boom_volume * boom_rho
print(f'Antenna boom mass = {boom_mass:.3f} kg each')
```

```
Antenna boom mass = 0.088 kg each
```

In [19]:
```
boom_length['stowed'] = 0.105  # assumption based on July 2022 CAD model
boom_area['stowed'] = boom_volume / boom_length['stowed']
boom_diam['stowed'] = boom_diam['deployed']  # approx guess
boom_wall['stowed'] = boom_area['stowed'] / (math.pi * boom_diam['stowed'])
```

Each antenna also has a tip piece. The mass and size are estimated here from the July 2022 CAD model.

In [20]:
```
ant_tip_mass = 0.029
ant_tip_length = 0.156
ant_tip_diam = boom_diam['deployed'] - boom_wall['deployed']
ant_tip_inertia_about_cg = ant_tip_mass/48 * (3*ant_tip_diam**2 + 4*ant_tip_length**2)
print(f'Antenna mass (boom + tip) = {boom_mass + ant_tip_mass:.3f} kg each')
```

```
Antenna mass (boom + tip) = 0.117 kg each
```

In [21]:
```
boom_root_radial_position = plate_od/2 - boom_length['stowed'] # where the antenna bas
ant_inertia = {}
for k in ('deployed', 'stowed'):
    boom_OD = boom_diam[k] + boom_wall[k] / 2
    boom_ID = boom_diam[k] - boom_wall[k] / 2
    boom_inertia_about_cg = boom_mass/48 * (3*boom_OD**2 + 3*boom_ID**2 + 4*boom_lengt
    boom_offset = boom_root_radial_position + boom_length[k] / 2
    ant_tip_offset = boom_root_radial_position + boom_length[k] - ant_tip_length/2
    boom_inertia = boom_inertia_about_cg + boom_mass * boom_offset**2
    ant_tip_inertia = ant_tip_inertia_about_cg + ant_tip_mass * ant_tip_offset**2
    ant_inertia[k] = boom_inertia + ant_tip_inertia
    print(f'Antenna inertia (boom + tip) = {ant_inertia[k]:.4f} kg/m^2 each ({k})')
```

```
Antenna inertia (boom + tip) = 0.5781 kg/m^2 each (deployed)
Antenna inertia (boom + tip) = 0.0044 kg/m^2 each (stowed)
```

Antenna deployers

As of July 2022, the deployers and attached hardware (including pre-amp?) are assumed to be ~ 0.75 kg per antenna. This value will change somewhat as the design is refined.

For the purposes of this calculation, the deployer geometry is treated as a cuboid with side lengths estimated based on the stowed antenna length.

In [22]:
```
deployer_mass = 0.75
deployer_length = boom_length['stowed'] * 3
deployer_width = boom_length['stowed']
deployer_radial_position = plate_od / 2
deployer_inertia_about_cg = deployer_mass / 12 * (deployer_width**2 + deployer_length*
deployer_inertia = deployer_inertia_about_cg + deployer_mass * deployer_positic
print(f'Deployer mass = {deployer_mass:.3f} kg (each)')
print(f'Deployer inertia = {deployer_inertia:.4} kg/m^2 (each)')
```

```
Deployer mass = 0.750 kg (each)
Deployer inertia = 0.05377 kg/m^2 (each)
```

Central shaft and bearings

These rotating components are lumped together and approximated as a single tube of metal.

In [23]:
```
central_od = 0.080  # outer diameter
central_id = 0.070  # inner diameter
central_length = 0.020  # length
central_r1, central_r2 = central_id/2, central_od/2  # radii
central_rho = rho_SS
central_mass = central_rho * central_length * math.pi * (central_r2**2 - central_r1**2
central_inertia = 0.5 * central_mass * (central_r1**2 + central_r2**2)
print(f'Central shaft and bearing mass = {central_mass:.3f} kg')
print(f'Central shaft and bearing inertia = {central_inertia:.4} kg/m^2')
```

```
Central shaft and bearing mass = 0.188 kg
Central shaft and bearing inertia = 0.0002662 kg/m^2
```

Parallel-axis transmission

The motor will be mounted off-axis and parallel to the central bearing.

In the present study (July 2022), details of this transmission are not considered. For code completeness, a gear ratio is included, but here set to 1:1. A simple torque reduction factor is assumed, accounting for frictional loss in this transmission.

In [24]:
```
# Note: The transmission ratio here does *not* include the internal gearing of the mot
# This value is only about the transmission between it and the turntable.
transmission_ratio = 1.0 / 1.0  # gearmotor output revolutions per turntable revolutio
transmission_efficiency = 0.90  # assumption based on typical roller chain drives
```

Motor shaft, gearhead, bearing

In the present study (July 2022), whose initial purpose is to define specifications for the motor, the internal details of the motor are not considered. They could be added to this study at a later date, after we have selected a specific motor model.

External dust seal

Some dust seal(s) will be required to prevent lunar dust from accessing the bearing and transmission. These impose some friction load on the assembly.

Here I assume the seal contact is made against a flat face by annular, thin-walled polyimide. In this approach, there would be one seal at the turntable rotation axis, and another at the motor output, covering the off-axis transmission components. (The motor may additionally have internal seals in its bearing at the output shaft, TBD.)

The seal at the central axis will bear either on the rotating turntable, or else be mounted to the turntable and bear on its opposing counterpart (i.e. the top plate or the central shaft support). Preload force will be relatively low, since only dust needs to be excluded.

Some comments are offered in another section about the option of alternatively, or additionally, having internal seals integral to the bearing. There are both advantages and disadvantages. It would be necessary for the bearing vendor to fabricate using a seal material with which we are comfortable at the lunar temperature extremes and in vacuum.

In [25]:
```
seal_contact_radius = 0.080  # annulus of contact for the seals
seal_contact_width = 0.003  # rough guess as to desirable contact width, will depend c
seal_contact_pressure_millibar = 5  # rough guess as to desirable clamping pressure (p
seal_contact_pressure = seal_contact_pressure_millibar * 1000
seal_contact_area = 2 * math.pi * seal_contact_radius * seal_contact_width
seal_clamping_force = seal_contact_pressure * seal_contact_area
print(f'External dust seal at radius {seal_contact_radius:.3f} m: clamping force = {se
```

```
External dust seal at radius 0.080 m: clamping force = 7.5 N
```

Datasheet values for the static and dynamic friction coefficient of Vespel SP-1 are listed at 0.29 and 0.35, respectively. I presume a fixed, static value of 0.35 for the purposes of this calculation, and estimate a fixed torque based on the assumed contact annulus.

In [26]:
```
seal_mu = 0.35
seal_torque = seal_mu * seal_contact_radius * seal_clamping_force
print(f'External dust seal static torque = {seal_torque:.3f} N*m = {seal_torque / Nm_p
```

```
External dust seal static torque = 0.211 N*m = 29.9 oz*in
```

Bearing friction

For the purposes of preliminary overall system torque calculations, I presume a bearing with its own integrated dust seal. This may not be the case, as discussed in more detail in the bearing selection section below. But presently, in sizing the motor and transmission, I assume selection of a single Type-X, nitrile double-sealed, stainless steel bearing, e.g. Kaydon WA025XP0. The vendor provides a static torque value for this bearing, given default lubrication and temperature conditions:

In [27]:
```
bearing_torque_ozin = 8.0  # oz*in
bearing_torque = bearing_torque_ozin * Nm_per_ozin
print(f'Central bearing static torque = {bearing_torque:.3f} N*m')
```

```
Central bearing static torque = 0.056 N*m
```

Harness

The primary elastic contributor to motor driving torque is the cable harness. Its torsional stiffness is estimated here by counting the number of conductors, assuming a diameter for each conductor, and then adding up their torsional stiffness plus their insulating coatings in parallel. The individual conductors are here treated as solid core, though in reality they would be stranded.

In [28]:
```
wires_per_antenna = 20
n_wires = n_ant * wires_per_antenna
wire_diam_mm = 0.35
```

```
wire_insul_wall_mm = 0.15  # wall thickness of insulator on wire
wire_diam = wire_diam_mm / 1000
wire_insul_wall = wire_insul_wall_mm / 1000
J_wire = math.pi/32 * wire_diam**4  # wire polar moment of inertia
J_insul = math.pi/32 * ((wire_diam + 2*wire_insul_wall)**4 - wire_diam**4)  # insulati
harness_length = 0.3  # estimated from July 2022 CAD model
shear_modulus = lambda E: E / (2*(1 + 0.3))  # approx shear modulus for typical poissc
insulated_wire_stiffness = (shear_modulus(E_Cu) * J_wire + shear_modulus(E_plastic) *
harness_stiffness = n_wires * insulated_wire_stiffness
harness_max_torque = harness_stiffness * max(rotation_range)
for unit, scale in {'N*m/rad': 1.0, 'N*mm/deg': 180/math.pi*1000, 'oz*in/deg': 180/mat
    print(f'Harness approx torsional stiffness = {harness_stiffness*scale:.4g} {unit}'
for unit, scale in {'N*m': 1.0, 'N*mm': 1000., 'oz*in': 1/Nm_per_ozin}.items():
    print(f'Harness max torque resistance = {harness_max_torque*scale:.4g} {unit}')
```

```
Harness approx torsional stiffness = 0.02097 N*m/rad
Harness approx torsional stiffness = 1202 N*mm/deg
Harness approx torsional stiffness = 170.2 oz*in/deg
Harness max torque resistance = 0.03477 N*m
Harness max torque resistance = 34.77 N*mm
Harness max torque resistance = 4.924 oz*in
```

Gear inertia

The vendor datasheet for Globe Motors A-1430, as an example, indicates a maximum gear inertia. While included here for completeness, in practice this value is negligible with respect to the overall system. (This fact is displayed further down, see printout in the "Known" torques calculation below.)

In [29]:
```
max_gear_inertia_ozinsec2 = 1.8e-6  # oz*in*sec^2, Globe A-1430
max_gear_inertia = max_gear_inertia_ozinsec2 * Nm_per_ozin  # kg*m^2
```

Performance

Our needs for rotational speed and acceleration are relatively low.

Speed

Repositioning will take on the order of minutes. The constraints imposed here are generally based on rough practical assumptions. There are no strong constraints at either the too-slow or too-fast ends of this range.

In [30]:
```
min_slew_time = 5.  # when going the maximum slew distance
max_slew_time = 300.  # when going the maximum slew distance
antibacklash_move_deg = 3.0
antibacklash_move = math.radians(antibacklash_move_deg)
max_slew_distance = total_rotation_range + antibacklash_move
min_allowable_speed = max_slew_distance / (max_slew_time)
max_allowable_speed = max_slew_distance / (min_slew_time)
print(f'Min allowable speed = {min_allowable_speed/radpersec_per_rpm:.3g} rpm = {math.
print(f'Max allowable speed = {max_allowable_speed/radpersec_per_rpm:.3g} rpm = {math.
```

```
Min allowable speed = 0.107 rpm = 0.6 deg/s.
Max allowable speed = 6.43 rpm = 38.6 deg/s.
```

Acceleration

Acceleration must not exceed the buckling strength of the extended antenna. Here we estimate the buckling critical load per Roark's 7th Edition:

16. Thin-walled circular tube under a transverse bending moment M (radius of tube $= r$)  $\frac{r}{t} > 10$	16a. No constraint	$M' = K\frac{E}{1-\nu^2}rt^2$ Here the theoretical value of K for pure bending and long tubes is 0.99. The average value of K determined by tests is 1.14, and the minimum value is 0.72. Except for very short tubes, length effect is negligible and a small transverse shear produces no appreciable reduction in M'. A very short cylinder under transverse (beam) shear may fail by buckling at neutral axis when shear stress there reaches a value of about $1.25\tau'$ for case 17a (Refs. 6, 14, 15)

In [31]:
```
buckling_design_safety_factor = 100  # stay conservative, since this is both Euler ins
tube_transverse_buckling_K = 0.72  # using minimum value here, to stay on conservative
boom_root_radial_position = plate_od
boom_critical_moment = tube_transverse_buckling_K * E_BeCu / (1 - nu_BeCu**2) * boom_]
boom_allowable_moment = boom_critical_moment / buckling_design_safety_factor
boom_allowable_accel = boom_allowable_moment / ant_inertia['deployed']
boom_allowable_accel_period = max_allowable_speed / boom_allowable_accel
print(f'Antenna critical buckling moment = {boom_critical_moment:.1f} N*m')
print(f'Applying safety factor of {buckling_design_safety_factor} --> allowable moment
print(f'--> max allowable acceleration = {boom_allowable_accel:.1f} rad/s^2 = {math.de
print(f'--> min allowable period of acceleration = {boom_allowable_accel_period:.3g} s
```

```
Antenna critical buckling moment = 4976.9 N*m
Applying safety factor of 100 --> allowable moment = 49.8 N*m
--> max allowable acceleration = 86.1 rad/s^2 = 4932.8 deg/s^2 = 13.7 rev/s^2
--> min allowable period of acceleration = 0.00783 sec
```

The boom buckling-limited acceleration is indeed many orders of magnitude faster than we expect any practical real-world system to perform, and hence is ignored for the remainder of the calculations.

We assert limits on nominal acceleration based on the margin of extra mechanical range we are mechanically providing the turntable. We prefer the system to be capable of fully accelerating within about twice that angular distance. This is not a hard physical constraint, just a practical consideration.

In [32]:
```
accel_dist = rotation_range_margin * 2.0
nom_accel = [v**2 / (2 * accel_dist) for v in [min_allowable_speed, max_allowable_spee
print(f'Nominal bounds on system acceleration rate = ({min(nom_accel):.3g}, {max(nom_a
assert max(nom_accel) <= boom_allowable_accel, f'max nominal acceleration is higher th
```

```
Nominal bounds on system acceleration rate = (0.000361, 1.3) rad/s^2 = (0.0207, 74.5)
°/s^2
```

Torque margin calculation

Resistive known torques

In [33]:
```
total_inertia = plate_inertia + n_ant * (ant_inertia['deployed'] + deployer_inertia) +
T_known_range = [total_inertia * a for a in nom_accel]
T_known_range_ozin = [T / Nm_per_ozin for T in T_known_range]
print(f'Total payload inertia (i.e. not including motor) = {total_inertia:.4g} kg*m^2'
```

```
print(f'(Note: max gear inertia {max_gear_inertia:.3g} kg*m^2 represents a fraction {m
print(f'Possible range for total "known" resistive torque @ min accel = {min(T_known_r
print(f'                                              ... @ max accel = {max(T_known_r

# Select a single nominal T_known
# Note that GEVS torque margins, applied later below, will add significant torque to t
# In other words, this is not the place to apply large margin.
T_known_margin = 0.01  # small, arbitrary fraction between the (wide-ranging) min and
T_known = T_known_margin * (max(T_known_range) - min(T_known_range)) + min(T_known_ran
T_known_ozin = T_known / Nm_per_ozin
print(f'\nNominal design value selected for total "known" resistive torque = {T_known:
```

```
Total payload inertia (i.e. not including motor) = 2.617 kg*m^2
(Note: max gear inertia 1.27e-08 kg*m^2 represents a fraction 4.9e-09 of total.)
Possible range for total "known" resistive torque @ min accel = 0.000945 N*m = 0.134
oz*in
                                              ... @ max accel = 3.4 N*m = 482 oz*in

Nominal design value selected for total "known" resistive torque = 0.035 N*m = 4.95 o
z*in
```

Resistive variable torques

In [34]:

```
T_static_friction = [bearing_torque, seal_torque + bearing_torque]  # range of options
T_friction_transmission_loss = [T * (1 - transmission_efficiency) for T in T_static_fr
T_known_transmission_loss = (1 - transmission_efficiency) * T_known
T_transmission_loss = [T_known_transmission_loss + T for T in T_friction_transmission_
T_variable = [min(T_static_friction) + min(T_transmission_loss),
              max(T_static_friction) + max(T_transmission_loss) + harness_max_torque]
print(f'Range for static friction torque = ({min(T_static_friction):.3f}, {max(T_stati
print(f'Range for transmission loss = ({min(T_transmission_loss):.3f}, {max(T_transmis
print(f'Range for "variable" resistive torque = ({min(T_variable):.3f}, {max(T_variabl
```

```
Range for static friction torque = (0.056, 0.268) N*m
Range for transmission loss = (0.009, 0.030) N*m
Range for "variable" resistive torque = (0.066, 0.333) N*m = (9.3, 47.1) oz*in
```

Minimum driving torque

We use the resistive known and variable torques, in combination with the GEVS safety factors, to determine the minimum allowable motor torque.

In [35]:

```
TM = 0.0  # set to 0 for minimum allowable, i.e. positive torque margin
T_avail_min = (TM + 1) * (FSk * T_known + FSv * max(T_variable))
print(f'For positive torque margin, with safety factors FSk = {FSk} and FSv = {FSv},\n
      f'minimum gearmotor torque shall be T_avail = {T_avail_min:.3g} N*m = {T_avail_m
```

```
For positive torque margin, with safety factors FSk = 2.0 and FSv = 4.0,
minimum gearmotor torque shall be T_avail = 1.4 N*m = 198 oz*in
```

Maximum driving torque (buckling constraint)

As discussed above, the acceleration rate to cause antenna boom buckling is many orders of magnitude outside what any practical motor in this application will achieve. This is confirmed below, by a simple scaling argument:

In [36]:
```
scaled_buckling_torque = boom_allowable_accel / (T_known / total_inertia) + min(T_vari
print(f'To even approach the boom buckling safety factor {buckling_design_safety_facto
      f'\ntorque would have to be >= {scaled_buckling_torque:.1f} N*m = {scaled_buckli
```

```
To even approach the boom buckling safety factor 100, available motor driving
torque would have to be >= 6444.3 N*m = 912588.2 oz*in
```

Appendix: Motor selection

As of July 2022, we have been presuming usage of Globe Motor A-1430. This model indeed is offered with reduction ratios that deliver 300 oz-in of torque. Therefore we can proceed further with this motor family.

At the nominal operating voltage, the Globe Motors have two armature winding options:

In [37]:
```
motor_voltage = 12.  # VDC
globe_armature = {'-15': {'no load speed (rpm)': [13500, 17000],
                          'max rated torque (oz*in)': 0.22,
                          'theoretical stall (oz*in)': 2.60,
                          'Kt (oz*in/A)': 0.95,
                          'R': 3.70,  # ohms
                         },
                  '-14': {'no load speed (rpm)': [10000, 13000],
                          'max rated torque (oz*in)': 0.33,
                          'theoretical stall (oz*in)': 2.00,
                          'Kt (oz*in/A)': 1.32,
                          'R': 6.46,  # ohms
                         },
                 }
```

Among enclosed type motors, the family includes numerous options. The 12 gearhead configurations with max continous torque >= 45 oz*in are tested below:

In [38]:
```
globe_gear = {'43A147': {'speed reduction ratio': 321,
                         'torque multiplier ratio': 130,
                         'length (in)': 3.11,
                         'max continuous torque (oz*in)': 45.,
                        },
              '43A148': {'speed reduction ratio': 485,
                         'torque multiplier ratio': 200,
                         'length (in)': 3.11,
                         'max continuous torque (oz*in)': 70.,
                        },
              '43A149': {'speed reduction ratio': 733,
                         'torque multiplier ratio': 300,
                         'length (in)': 3.11,
                         'max continuous torque (oz*in)': 100.,
                        },
              '43A150': {'speed reduction ratio': 1108,
                         'torque multiplier ratio': 450,
                         'length (in)': 3.11,
                         'max continuous torque (oz*in)': 150.,
                        },
              '43A151': {'speed reduction ratio': 1853,
                         'torque multiplier ratio': 600,
                         'length (in)': 3.28,
```

```
                    'max continuous torque (oz*in)': 200.,
                   },
         '43A152': {'speed reduction ratio': 2799,
                    'torque multiplier ratio': 900,
                    'length (in)': 3.28,
                    'max continuous torque (oz*in)': 300.,
                   },
         '43A153': {'speed reduction ratio': 4230,
                    'torque multiplier ratio': 1400,
                    'length (in)': 3.28,
                    'max continuous torque (oz*in)': 300.,
                   },
         '43A154': {'speed reduction ratio': 6391,
                    'torque multiplier ratio': 2100,
                    'length (in)': 3.28,
                    'max continuous torque (oz*in)': 300.,
                   },
         '43A155': {'speed reduction ratio': 10689,
                    'torque multiplier ratio': 2800,
                    'length (in)': 3.45,
                    'max continuous torque (oz*in)': 300.,
                   },
         '43A156': {'speed reduction ratio': 16150,
                    'torque multiplier ratio': 4200,
                    'length (in)': 3.45,
                    'max continuous torque (oz*in)': 300.,
                   },
         '43A157': {'speed reduction ratio': 24403,
                    'torque multiplier ratio': 6400,
                    'length (in)': 3.45,
                    'max continuous torque (oz*in)': 300.,
                   },
         '43A158': {'speed reduction ratio': 36873,
                    'torque multiplier ratio': 9700,
                    'length (in)': 3.45,
                    'max continuous torque (oz*in)': 300.,
                   },
        }
```

Speed is calculated by a linear assumption for the torque/speed curve, i.e.:

$\omega_r \approx (1 - \frac{\tau_r}{\tau_o})\omega_o$

where:

ω_r = angular speed of rotor

ω_o = no load speed

τ_r = torque of rotor

τ_o = stall torque

Electrical power consumed, mechanical power output, and efficiency of this conversion are estimated:

$$P_{elec} \approx IV + I^2R = \frac{\tau_r}{K_t}V + \left(\frac{\tau_r}{K_t}\right)^2 R$$

$$P_{mech} = \tau_g\omega_g \approx \frac{\beta_\tau}{\beta_\omega}\tau_r\omega_r$$

$$\eta = \frac{P_{mech}}{P_{elec}} = \frac{\beta_\tau}{\beta_\omega}\frac{K_t}{V}\omega_r$$

where:

I = current

V = voltage

R = resistance

K_t = motor torque constant (N*m/A or oz*in/A)

τ_g = torque at gearhead output shaft

ω_g = angular speed at gearhead output shaft

$\beta_\tau = \frac{\tau_g}{\tau_r}$ = torque multiplier ratio of gearhead

$\beta_\omega = \frac{\omega_r}{\omega_g}$ = speed reduction ratio of gearhead

In [39]:
```
avg_harness_torque = harness_max_torque / 2
estim_loads = {'min continuous tau_g (oz*in)': (min(T_static_friction) + min(T_frictic
               'max continuous tau_g (oz*in)': (max(T_static_friction) + max(T_frictic
               'min intermittent tau_g (oz*in)': (T_known + min(T_variable)) / Nm_per_
               'max intermittent tau_g (oz*in)': (T_known + max(T_variable)) / Nm_per_
              }
gearmotor = []
for a, arm in globe_armature.items():
    tau0_ozin = arm['theoretical stall (oz*in)']
    w0_rpm = max(arm['no load speed (rpm)'])  # pick one of the vendor values for simp
    Kt_ozinperA = arm['Kt (oz*in/A)']
    for g, gear in globe_gear.items():
        gearmotor += [{'part': f'{g}{a}'}]
        gearmotor[-1]['arm'] = arm
        gearmotor[-1]['gear'] = gear
        beta_t = gear['torque multiplier ratio']
        beta_w = gear['speed reduction ratio']
        gearmotor[-1]['rated tau_r (oz*in)'] = arm['max rated torque (oz*in)']  # prac
        gearmotor[-1]['rated tau_g (oz*in)'] = gearmotor[-1][f'rated tau_r (oz*in)'] *
        for prefix in ['rated'] + ['min continuous', 'max continuous', 'min intermitte
            tau_g_ozin = gearmotor[-1][f'{prefix} tau_g (oz*in)'] if prefix == 'rated'
            tau_r_ozin = tau_g_ozin / beta_t
            tau_r = tau_r_ozin * Nm_per_ozin
            I = tau_r_ozin / Kt_ozinperA
            VI = I * motor_voltage
            w_r_rpm = (1 - tau_r_ozin / tau0_ozin) * w0_rpm
            w_r = w_r_rpm * radpersec_per_rpm
            gearmotor[-1][f'{prefix} tau_r (oz*in)'] = tau_r_ozin
            gearmotor[-1][f'{prefix} I'] = I
            gearmotor[-1][f'{prefix} P_elec'] = VI + I**2 * arm['R']
```

```
            gearmotor[-1][f'{prefix} P_mech'] = beta_t / beta_w * tau_r * w_r
            gearmotor[-1][f'{prefix} w_r (rpm)'] = w_r_rpm
            gearmotor[-1][f'{prefix} w_g (rpm)'] = w_r_rpm / beta_w
            gearmotor[-1][f'{prefix} efficiency'] = gearmotor[-1][f'{prefix} P_mech']
        gearmotor[-1]['gearhead continuous torque safety factor'] = gear['max continuc
        gearmotor[-1]['gearhead intermittent torque safety factor'] = 2 * gear['max cc
```

From this list, we select those motors which pass requirements on:

- continuous torque limit (per vendor datasheet)
- intermittent torque (per vendor datasheet)
- max and min design speeds (see section above)

In [40]:

```
torque_sf_tol = 0.1  # allow a bit of tolerance here for borderline cases, since in pr
continuous_torque_ok, intermittent_torque_ok, max_speed_ok, min_speed_ok = set(), set(
for idx, g in enumerate(gearmotor):
    if g['gearhead continuous torque safety factor'] >= (1.0 - torque_sf_tol):
        continuous_torque_ok.add(idx)
    if g['gearhead intermittent torque safety factor'] >= (1.0 - torque_sf_tol):
        intermittent_torque_ok.add(idx)
    if g['max continuous w_g (rpm)'] * radpersec_per_rpm <= max_allowable_speed:
        max_speed_ok.add(idx)
    if g['min continuous w_g (rpm)'] * radpersec_per_rpm >= min_allowable_speed:
        min_speed_ok.add(idx)
selected_idxs = continuous_torque_ok & intermittent_torque_ok & max_speed_ok & min_spe
print(f'Selected {len(selected_idxs)} motors, summarized below.')
```

```
Selected 3 motors, summarized below.
```

In [41]:

```
for idx in sorted(selected_idxs):
    gm = gearmotor[idx]
    print(f'\n{horiz_rule}\n')
    print(f'Part: {gm["part"]}')
    print(f'Speed reduction ratio = {gm["gear"]["speed reduction ratio"]}')
    for kind in ['continuous', 'intermittent']:
        print(f'Gearhead {kind} torque safety factor = {gm[f"gearhead {kind} torque sa
    for prefix, description in {'rated': 'Motor is rated for',
                                'min continuous': 'Estimated lows during continuous operatior
                                'max continuous': 'Estimated highs during continuous operatic
                                'min intermittent': 'Estimated lows during intermittent opera
                                'max intermittent': 'Estimated highs during intermittent oper
                               }.items():
        print('')
        print(f'{description}:')
        tau_g_ozin = gm[f"{prefix} tau_g (oz*in)"] if prefix == 'rated' else estim_loa
        print(f'{tab}Output torque = {tau_g_ozin*Nm_per_ozin:.3f} N*m = {tau_g_ozin:.1
        print(f'{tab}Output speed = {gm[f"{prefix} w_g (rpm)"]:.3f} rpm = {math.degree
        print(f'{tab}Power consumption = {gm[f"{prefix} P_elec"]:.3f} W')

    for prefix in ['min', 'max']:
        print('')
        print(f'Max slew ({math.degrees(max_slew_distance):.1f}{deg}) at {prefix.upper
        w_g = gm[f'{prefix} continuous w_g (rpm)'] * radpersec_per_rpm
        continuous_tau_g = estim_loads[f'{prefix} continuous tau_g (oz*in)'] * Nm_per_
        intermittent_tau_g = estim_loads[f'{prefix} intermittent tau_g (oz*in)'] * Nm_
        accel_avg_tau_g = (continuous_tau_g + intermittent_tau_g) / 2
        accel_avg = accel_avg_tau_g / total_inertia
        accel_time =  w_g / accel_avg
```

```
        accel_energy = accel_time * gm[f'{prefix} intermittent P_elec']
        accel_distance = 0.5 * accel_avg * accel_time**2
        coast_distance = max_slew_distance - accel_distance  # ignoring decel distance
        coast_time = coast_distance / w_g
        coast_energy = coast_time * gm[f'{prefix} continuous P_elec']
        total_est_time = coast_time + accel_time
        print(f'{tab}total time = {total_est_time:.1f} sec = {total_est_time/60:.1f} m
        print(f'{tab}total energy = {coast_energy + accel_energy:.1f} J')
```

```
----------

Part: 43A152-15
Speed reduction ratio = 2799
Gearhead continuous torque safety factor = 1.52 (must be ~ 1 or greater)
Gearhead intermittent torque safety factor = 11.53 (must be ~ 1 or greater)

Motor is rated for:
    Output torque = 1.398 N*m = 198.0 oz*in
    Output speed = 5.560 rpm = 33.36 deg/sec
    Power consumption = 2.977 W

Estimated lows during continuous operation:
    Output torque = 0.080 N*m = 11.3 oz*in
    Output speed = 6.044 rpm = 36.27 deg/sec
    Power consumption = 0.159 W

Estimated highs during continuous operation:
    Output torque = 0.312 N*m = 44.1 oz*in
    Output speed = 5.959 rpm = 35.75 deg/sec
    Power consumption = 0.629 W

Estimated lows during intermittent operation:
    Output torque = 0.101 N*m = 14.2 oz*in
    Output speed = 6.037 rpm = 36.22 deg/sec
    Power consumption = 0.201 W

Estimated highs during intermittent operation:
    Output torque = 0.368 N*m = 52.1 oz*in
    Output speed = 5.938 rpm = 35.63 deg/sec
    Power consumption = 0.744 W

Max slew (193.0°) at MIN speed:
    total time = 14.5 sec = 0.2 min
    total energy = 3.1 J

Max slew (193.0°) at MAX speed:
    total time = 7.8 sec = 0.1 min
    total energy = 5.5 J

----------

Part: 43A153-15
Speed reduction ratio = 4230
Gearhead continuous torque safety factor = 0.97 (must be ~ 1 or greater)
Gearhead intermittent torque safety factor = 11.53 (must be ~ 1 or greater)

Motor is rated for:
    Output torque = 2.175 N*m = 308.0 oz*in
    Output speed = 3.679 rpm = 22.07 deg/sec
    Power consumption = 2.977 W

Estimated lows during continuous operation:
    Output torque = 0.080 N*m = 11.3 oz*in
    Output speed = 4.006 rpm = 24.04 deg/sec
    Power consumption = 0.102 W

Estimated highs during continuous operation:
    Output torque = 0.312 N*m = 44.1 oz*in
    Output speed = 3.970 rpm = 23.82 deg/sec
```

```
    Power consumption = 0.402 W

Estimated lows during intermittent operation:
    Output torque = 0.101 N*m = 14.2 oz*in
    Output speed = 4.003 rpm = 24.02 deg/sec
    Power consumption = 0.129 W

Estimated highs during intermittent operation:
    Output torque = 0.368 N*m = 52.1 oz*in
    Output speed = 3.961 rpm = 23.77 deg/sec
    Power consumption = 0.475 W

Max slew (193.0°) at MIN speed:
    total time = 14.1 sec = 0.2 min
    total energy = 1.8 J

Max slew (193.0°) at MAX speed:
    total time = 9.7 sec = 0.2 min
    total energy = 4.1 J

----------

Part: 43A152-14
Speed reduction ratio = 2799
Gearhead continuous torque safety factor = 1.01 (must be ~ 1 or greater)
Gearhead intermittent torque safety factor = 11.53 (must be ~ 1 or greater)

Motor is rated for:
    Output torque = 2.097 N*m = 297.0 oz*in
    Output speed = 3.878 rpm = 23.27 deg/sec
    Power consumption = 3.404 W

Estimated lows during continuous operation:
    Output torque = 0.080 N*m = 11.3 oz*in
    Output speed = 4.615 rpm = 27.69 deg/sec
    Power consumption = 0.114 W

Estimated highs during continuous operation:
    Output torque = 0.312 N*m = 44.1 oz*in
    Output speed = 4.531 rpm = 27.18 deg/sec
    Power consumption = 0.455 W

Estimated lows during intermittent operation:
    Output torque = 0.101 N*m = 14.2 oz*in
    Output speed = 4.608 rpm = 27.65 deg/sec
    Power consumption = 0.145 W

Estimated highs during intermittent operation:
    Output torque = 0.368 N*m = 52.1 oz*in
    Output speed = 4.510 rpm = 27.06 deg/sec
    Power consumption = 0.538 W

Max slew (193.0°) at MIN speed:
    total time = 14.0 sec = 0.2 min
    total energy = 2.0 J

Max slew (193.0°) at MAX speed:
    total time = 8.9 sec = 0.1 min
    total energy = 4.4 J
```

Among these, I select the motor/gear combination with lower max speed and fewer gear stages: **43A152-14**

Appendix: Bearings selection

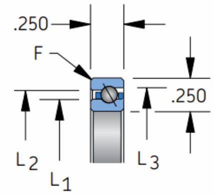
Bearing type and size

The preliminary design (July 2022) packaging acommodates a pair of Kaydon KA025AR0 bearings:

KA Series

KAYDON Bearing Number	Dimensions in Inches					Capacities in Pounds[1]					Approx. Wt. in lbs.
	Size		Land Diameters			Dynamic			Static[2]		
	Bore	Outside Dia.	L1	L2	C'Bore L3	KAYDON Radial	ISO Radial[3]	Thrust	Radial	Thrust	
▸KA020AR0	2.000	2.500	2.186	2.314	2.369	405	1,065	960	790	2,280	.10
▸KA025AR0	2.500	3.000	2.686	2.814	2.869	459	1,150	1,100	960	2,780	.12
▸KA030AR0	3.000	3.500	3.186	3.314	3.367	507	1,225	1,230	1,140	3,290	.14
▸KA035AR0	3.500	4.000	3.686	3.814	3.867	552	1,292	1,350	1,310	3,790	.17
▸KA040AR0	4.000	4.500	4.186	4.314	4.367	595	1,353	1,470	1,490	4,300	.19
▸KA042AR0	4.250	4.750	4.436	4.564	4.615	616	1,382	1,530	1,580	4,550	.20
▸KA045AR0	4.500	5.000	4.686	4.814	4.865	637	1,410	1,580	1,660	4,810	.21
▸KA047AR0	4.750	5.250	4.936	5.064	5.115	657	1,437	1,640	1,750	5,060	.22
▸KA050AR0	5.000	5.500	5.186	5.314	5.365	676	1,463	1,690	1,840	5,310	.23
▸KA055AR0	5.500	6.000	5.686	5.814	5.863	715	1,513	1,800	2,020	5,820	.25
▸KA060AR0	6.000	6.500	6.186	6.314	6.363	752	1,561	1,900	2,190	6,320	.28
▸KA065AR0	6.500	7.000	6.686	6.814	6.861	788	1,605	2,000	2,370	6,830	.30
▸KA070AR0	7.000	7.500	7.186	7.314	7.361	823	1,648	2,100	2,540	7,340	.32
▸KA075AR0	7.500	8.000	7.686	7.814	7.861	857	1,689	2,190	2,720	7,840	.34
▸KA080AR0	8.000	8.500	8.186	8.314	8.359	890	1,728	2,280	2,890	8,350	.36
KA090AR0	9.000	9.500	9.186	9.314	9.357	954	1,802	2,470	3,240	9,360	.41
▸KA100AR0	10.000	10.500	10.186	10.314	10.355	1,014	1,871	2,640	3,590	10,370	.45
KA110AR0	11.000	11.500	11.186	11.314	11.353	1,072	1,936	2,810	3,940	11,380	.50
KA120AR0	12.000	12.500	12.186	12.314	12.349	1,128	1,998	2,970	4,290	12,390	.54

Circular pocket separator 1/8" balls



F = .025[4]
Bearing corners are normally chamfered

1 Capacities listed are not simultaneous. For combined loading see discussion of Bearing Selection and Load Analysis. Dynamic capacities are based upon 1 million revolutions of L10 life. Published capacities do not apply to hybrid series bearings P, X, and Y - contact Kaydon product engineering for values.
2 Static capacities are non-brinell limits based on rigid support from the shaft and housing.
3 ISO Radial ratings are calculated per ISO 281:1990. They are included for comparison only (refer to Page 95).
4 "F" is the maximum shaft or housing fillet radius the bearing corners will clear.

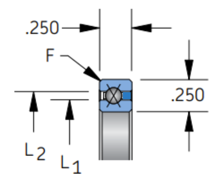
This is a thin section, angular contact, open bearing, with bore 2.5\" (63.5 mm), O.D. 3.0\" (76.2 mm), and thickness 0.25\" (6.35 mm). Mass is low, ~0.12 lbs = 55 g. We utilize the common design pattern of mounting in pairs, to provide tilt resistance.

Stainless steel options (may have custom lead-times and will be more expensive) are available. Replace "K" with "S" in the part number.

Kaydon also offers an attractive "Type X" four-point contact bearing. We have previously used such a bearing (at a much larger scale) in the Dark Energy Spectroscopic Instrument (DESI) ADC rotator mechanism. The type X controls 5 degrees of freedom in a single unit, rather than the typical angular contact duplex. This has the advantage of fewer parts and less weight, as well as removing the need to control thrust preload in the mounting between the two separate bearing units. A type X unit of similar package size as KA025AR0 would be KA025XP0:

KA Series											
KAYDON Bearing Number	Dimensions in Inches				Capacities[1]						Approx. Wt. in lbs.
	Size		Land Diameters		Dynamic			Static[2]			
	Bore	Outside Dia.	L_1	L_2	Radial (lbs)	Thrust (lbs)	Moment (in-lbs)	Radial (lbs)	Thrust (lbs)	Moment (in-lbs)	
▸KA020XP0	2.000	2.500	2.186	2.314	514	790	434	680	1,710	770	.10
▸KA025XP0	2.500	3.000	2.686	2.814	583	910	601	830	2,090	1,150	.13
KA027XP0	2.750	3.250	2.936	3.064	614	960	690	910	2,275	1,365	.14
▸KA030XP0	3.000	3.500	3.186	3.314	643	1,010	785	990	2,470	1,600	.15
▸KA035XP0	3.500	4.000	3.686	3.814	701	1,110	986	1,140	2,850	2,130	.18
▸KA040XP0	4.000	4.500	4.186	4.314	756	1,210	1,205	1,290	3,220	2,740	.19
▸KA042XP0	4.250	4.750	4.436	4.564	783	1,260	1,321	1,370	3,410	3,070	.20
▸KA045XP0	4.500	5.000	4.686	4.814	809	1,310	1,441	1,440	3,600	3,420	.22
▸KA047XP0	4.750	5.250	4.936	5.064	834	1,350	1,565	1,520	3,790	3,790	.23
▸KA050XP0	5.000	5.500	5.186	5.314	859	1,400	1,693	1,590	3,980	4,180	.24
▸KA055XP0	5.500	6.000	5.686	5.814	908	1,480	1,959	1,750	4,360	5,020	.25
▸KA060XP0	6.000	6.500	6.186	6.314	955	1,570	2,240	1,900	4,740	5,930	.28
▸KA065XP0	6.500	7.000	6.686	6.814	1,001	1,650	2,535	2,050	5,120	6,910	.30
▸KA070XP0	7.000	7.500	7.186	7.314	1,046	1,730	2,844	2,200	5,500	7,980	.31
▸KA075XP0	7.500	8.000	7.686	7.814	1,089	1,810	3,165	2,350	5,880	9,120	.34
▸KA080XP0	8.000	8.500	8.186	8.314	1,131	1,890	3,499	2,500	6,260	10,330	.38
▸KA090XP0	9.000	9.500	9.186	9.314	1,212	2,040	4,204	2,810	7,020	12,990	.44
▸KA100XP0	10.000	10.500	10.186	10.314	1,289	2,180	4,956	3,110	7,780	15,940	.50
KA110XP0	11.000	11.500	11.186	11.314	1,362	2,320	5,750	3,410	8,540	19,210	.52
▸KA120XP0	12.000	12.500	12.186	12.314	1,433	2,450	6,587	3,720	9,300	22,770	.56

Snap-over separator 1/8" balls



F = .025[3]
Bearing corners are normally chamfered

1 Capacities listed are not simultaneous. For combined loading see discussion of Bearing Selection and Load Analysis. Dynamic capacities are based upon 1 million revolutions of L10 life. Published capacities do not apply to hybrid series bearings P, X, and Y - contact Kaydon product engineering for values.
2 Static capacities are non-brinell limits based on rigid support from the shaft and housing.
3 "F" is the maximum shaft or housing fillet radius the bearing corners will clear.
▸ Popular item

Again, replace "K" with "S" for equivalent stainless option.

External vs internal bearing seals

For these open bearings, we would make a dust seal that rides on the shaft and/or flat face. Call this an "external" seal. It has the advantages of being:

- independent from the bearing selection and procurement
- easily replaceable
- visible and inspectable
- material of our choice (i.e. robust, low cte, temperature tolerant material like polyimide)

We can alternatively purchase a bearing with integrated seals. Call this an "internal" seal. It has the advantages of:

- lower part count
- lower mass
- more compact packaging

Again taking Kaydon as an example bearing manufacturer, their standard seal material is nitrile rubber. This would need to be qualified for our temperature range (100 K - 400 K). Kaydon does offer customization options in alternate seal materials, but we have not yet checked whether polyimide in particular would work for them. Several models Kaydon offers with an integrated double-seal are given in this table:

Kaydon part number	Dimensions in inches				Capacities[1]						Limiting speeds (RPM)*	Torque max. no load (in-oz)[3]	Approx. weight (lbs)
	Bore	Outside dia.	Land dia. L_1	Land dia. L_2	Dynamic			Static[2]					
					Radial (lbs)	Thrust (lbs)	Moment (in-lbs)	Radial (lbs)	Thrust (lbs)	Moment (in-lbs)			
JA020XP0	2.000	2.500	2.148	2.356	514	790	434	680	1,710	770	1,500	6	0.10
JA025XP0	2.500	3.000	2.648	2.856	583	910	601	830	2,090	1,150	1,200	8	0.12
JA030XP0	3.000	3.500	3.148	3.356	643	1,010	785	990	2,470	1,600	830	12	0.14
JA035XP0	3.500	4.000	3.648	3.856	701	1,110	986	1,140	2,850	2,130	710	16	0.17
JA040XP0	4.000	4.500	4.148	4.356	756	1,210	1,205	1,290	3,220	2,740	620	20	0.19
JA042XP0	4.250	4.750	4.398	4.606	783	1,260	1,321	1,370	3,410	3,070	580	24	0.20
JA045XP0	4.500	5.000	4.648	4.856	809	1,310	1,441	1,440	3,600	3,420	550	28	0.21
JA047XP0	4.750	5.250	4.898	5.106	834	1,350	1,565	1,520	3,790	3,790	520	32	0.22
JA050XP0	5.000	5.500	5.148	5.356	859	1,400	1,693	1,590	3,980	4,180	500	36	0.23
JA055XP0	5.500	6.000	5.648	5.856	908	1,480	1,959	1,750	4,360	5,020	450	44	0.25
JA060XP0	6.000	6.500	6.148	6.356	955	1,570	2,240	1,900	4,740	5,930	330	52	0.28
JA065XP0	6.500	7.000	6.648	6.856	1,001	1,650	2,535	2,050	5,120	6,910	300	61	0.30
JA070XP0	7.000	7.500	7.148	7.356	1,046	1,730	2,844	2,200	5,500	7,980	280	70	0.31
JA075XP0	7.500	8.000	7.648	7.856	1,089	1,810	3,165	2,350	5,880	9,120	260	80	0.34

Notes

1 Capacities listed are not simultaneous. For combined loading see discussion of Bearing Selection and Load Analysis in the Kaydon Reali-Slim® bearing catalog. Dynamic capacities are based upon 1 million revolutions of L_{10} life. Published capacities do not apply to hybrid series bearings P, X, and Y. Contact Kaydon product engineering for values.

2 Static capacities are non-brinell limits based on rigid support from the shaft and housing.

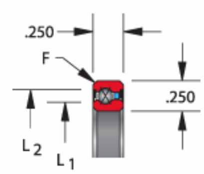
3 Torque figures shown are for single bearings with standard lubricant at room temperature and under 5 pounds thrust load.

4 "F" is the maximum shaft or housing fillet radius the bearing corners will clear.

* Values apply to bearings loaded up to 20% of their dynamic capacity.

Sealed series bearings are supplied with general purpose grease, satisfactory for operating temperatures of -65°F to +250°F (-54°C to +121°C). Other lubricants are available on special order.

Snap-over separator
1/8" balls



[4]F = 0.025
Bearing corners are normally chamfered

The Kaydon line-up does not have sealed bearings in angular contact configurations.

For sealed bearings, replace "J" with "W" in the part number for the stainless option.

Bearing seal materials

If we fabricate our own seals, one might consider using Vespel SP-3. This is a 15% MoS_2-filled polyimide with a long history of use in space applications, with low creep, high strength, and low coefficient of thermal expansion (for a polymer), and which should survive the temperature extremes.

A concern I have is that the friction coefficient of SP-3 in vacuum is reported to be very low (0.03) in the Dupont datasheet. Normally lower friction is "good" in a bearing, however in our design, having some consistent friction is helpful, to guarantee stability of the position of the turntable stable when powered off. So we probably rather prefer having a consistent friction whether testing in lab air or operating in vacuum. In this respect, unfilled Vespel SP-1 may be a simpler and better choice. However, the DuPont datasheet does not specifically list a vacuum friction coefficient, so this bears some further investigation.

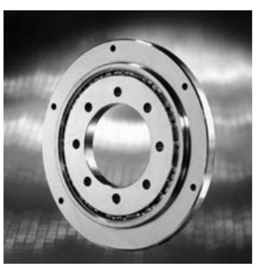
Graphite-filled polyimide grades would not be chosen, since the graphite lubricant can in fact become abrasive in a moisture-free environment.

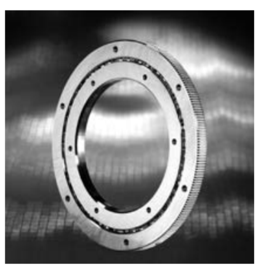
Turntable bearings

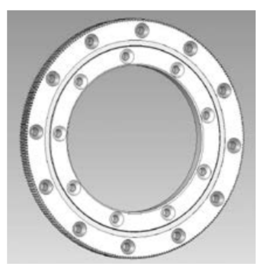
There are some bearings available with more integrated turntable functionality, for example including an external gear profile. An attractive option may be Kaydon T01-00325EAA:

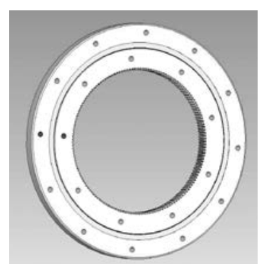
Four-point contact bearing (Reali-Slim TT® series)								
Kaydon Bearings basic part number	Dynamic			Static			Static torque (in-lbs)	Weight (lbs)
	Radial (lbs)	Thrust (lbs)	Moment (in-lbs)	Radial (lbs)	Thrust (lbs)	Moment (in-lbs)		
T01-00225	520	790	440	680	1,710	770	3.4	0.35
T01-00275	580	910	600	830	2,090	1,150	4.4	0.43
T01-00325	640	1,010	780	990	2,470	1,600	5.5	0.50
T01-00375	700	1,110	980	1,140	2,850	2,130	6.5	0.59
T01-00425	750	1,210	1,200	1,290	3,220	2,740	7.4	0.67

External gear										
Kaydon Bearings part number with through holes	Bore (in)	Gear O.D. (in)	Inner land (in)	Outer land (in)	Inner bolt circle (in)	Number of holes	Outer bolt circle (in)	Number of holes	Gear pitch diameter (in)	Number of teeth
T01-00225EAA	1.500	3.078	2.148	2.356	1.813	6	2.688	8	3.047	195
T01-00275EAA	2.000	3.578	2.648	2.856	2.313	8	3.188	10	3.547	227
T01-00325EAA	2.500	4.078	3.148	3.356	2.813	9	3.688	12	4.047	259
T01-00375EAA	3.000	4.578	3.648	3.856	3.313	10	4.188	14	4.547	291
T01-00425EAA	3.500	5.078	4.148	4.356	3.813	12	4.688	15	5.047	323


No gear with through holes


External gear with tapped holes


Externally geared bearing with countersunk holes


Internal gear with tapped holes

These turntables are not off-the-shelf parts. Cost and lead-time would be TBD. Performance is not particularly any better than the other options; the attraction here would be the compact packaging. The gearing would need some exterior protection from lunar dust.

References

- NASA General Environmental Verification Standards (GEVS)

- Kaydon turntable bearings
- Kaydon sealed, slim bearings