Low-Power Earth Horizon Sensor for Small Satellites

ECE 4530 - Final Project Report - Dr. Molnar

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Abstract

This project addresses the need for a robust and reliable method for low Earth orbit (LEO) satellites to orient themselves toward Earth's horizon. The proposed solution involves designing a differential amplifier with sufficient gain to detect and amplify the difference in photogenerated current from two photodiodes. The system includes a photodiode connected to a current mirror, which amplifies the photocurrent and feeds it into two simple differential amplifiers. We assume the max photocurrent to be 50 nA, modeled based on a real photodiode, and the current mirror to have a current gain of 15. The outputs of the amplifier produce a voltage difference proportional to the satellite's angle relative to the horizon.

We assume a lens with a specific refractive index such that only one photodiode is creating a photocurrent when aligned with the horizon. When the satellite is aligned with the horizon, the output voltage difference is 1.51 V, serving as the target for maintaining proper orientation. If misalignment occurs, the voltage difference drops to zero, signaling to the satellite to adjust its orientation in one rotational axis until the desired 1.51 V difference is restored. This voltage signal can serve as an input for feedback control systems to adjust pitch or yaw, ensuring continuous alignment with Earth's horizon.

Introduction

Horizon detection is needed as a secondary option for when sensors such as Inertial Measurement Units (IMU) fail. Maintaining the satellite level to Earth's horizon is crucial for signal transmission and reception, imaging or climate monitoring, and essential for precise navigation of LEO satellites. Thus, it is seen as necessary to have a system that is reliable and can be used either as a primary or secondary system to align oneself with Earth's horizon.

This project explores the design and simulation of two simple differential amplifiers that return a voltage difference between the outputs relative to the alignment toward Earth's horizon. While also maintaining a very low power consumption (< 5 mW) and an area low enough to fit in an incredibly small satellite ($\sim 10^{-6}$ m). For simplicity, we assumed that the circuit would work only on the sunlit side of the Earth at all times as discussed in later sections. The circuit was also designed to work off of 3.3V, a common voltage readily found on small satellites as it is already used by onboard microcontrollers and sensors.

The primary objective of this project is to meet these specifications while ensuring that the output voltages vary by a voltage level for which we can confidently say whether the satellite is facing the horizon or not. The subsequent sections will detail the system design and specifications, circuit schematics, circuit layout, and the challenges and lessons learned throughout the project.

System Design

To implement the horizon sensor we focused on designing the system to be as simple as possible. To do this we made three assumptions: (1) Satellite is in LEO at approximately 1000 km. (2) The horizon sensor only works on the sunlit side of Earth for the lens optics to work. (3) The horizon sensor only needs to pitch to orient towards Earth; in other words, there is only one degree of freedom (DOF) for the system.

The final goal of the system is to orient the satellite to point towards Earth's horizon. To do this, we designed it in a way that produces an output that will activate the actuator such as a gyroscope when the satellite is currently not oriented to Earth's horizon. When the satellite is aligned to Earth's horizon, the actuator should not be activated. For simplicity, we only are orienting the satellite through the pitch axis although, in reality, this would need to be done in multiple rotational axes. In addition, damping should be applied to help reduce the oscillation when the satellite overshoots the horizon.

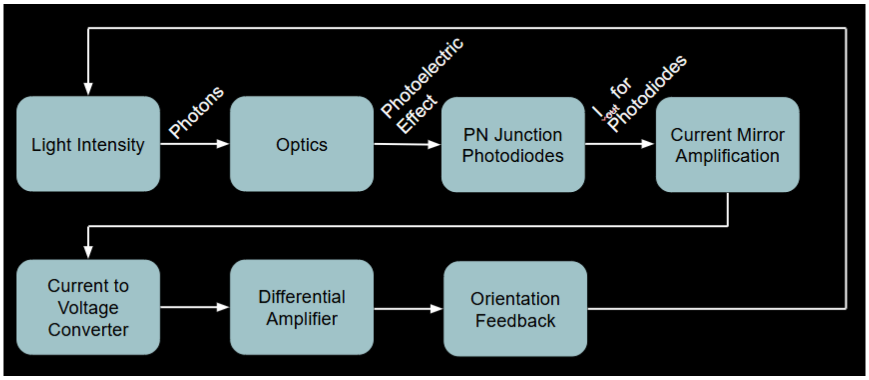


Figure 1: System Block Diagram

As shown in the system diagram above, first the incident light on the sensor passes through a lens which is then received by either of the two photodiodes. Due to the photoelectric effect, the photodiodes will produce a current proportional to their area and the incident light intensity. This current is fairly small so it is amplified 15 times using a current mirror. Each photodiode's amplified current is then converted to a voltage through a 50 kΩ resistor. Each photodiode's voltage is input into a differential amplifier which amplifies the difference between the two signals to produce a reasonable output voltage that can be used to control the actuator. This process repeats providing continuous feedback to the satellite's orientation unless the sensor is powered off.

One idea we had to control the actuator was to use a MOSFET switch with the output powering the actuator. When in saturation (Vgs > Vth and Vd > Vg - Vth), the MOSFET would pull the output closer to ground and high to Vdd when in cutoff (Vgs < Vth ~ 0.5 V). This would require that the output of the differential amplifier be less than Vth or 0.5 V to power the actuator. To stop powering the actuator the output would need to be above 0.5 V.

For our system, we use a lens with 1x magnification to minimize the sensor and optics footprint. There are three possible cases for the orientation of the satellite relative to the Earth. We assume that there is a fixed reference frame about the satellite:

- Case 1: The sensor is pointing directly at the horizon, which is the result we are aiming for. This means that half of the sensor's FOV is occupied by light reflected off of the Earth and the second half is occupied by light reflected off.
- Case 2: The sensor can be pointing directly at the Earth, in which case the whole FOV of the sensor is receiving light reflected off of the Earth thus both photodiodes are outputting current.
- Case 3: The sensor can be pointing out into space completely facing away from the Earth such that it is not at all in the sensor's field of view (FOV). This means that neither of the photodiodes is outputting any current as there is no incident light reflected from the Earth.

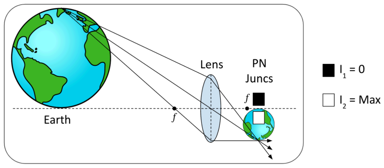
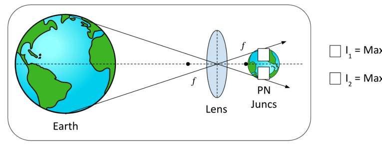
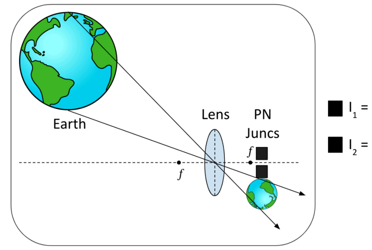
Case 1: Perfect Horizon Alignment	Case 2: Misaligned Directly Facing Earth	Case 3: Misaligned Facing Outer Space
		

Table 1: Possible Cases for Sensor Orientation

Taking these 3 edge cases into account, the following relationship between the photodiode currents and orientation is derived, where φ is the angle between the center of the earth and the center of the lens as shown by the image below.

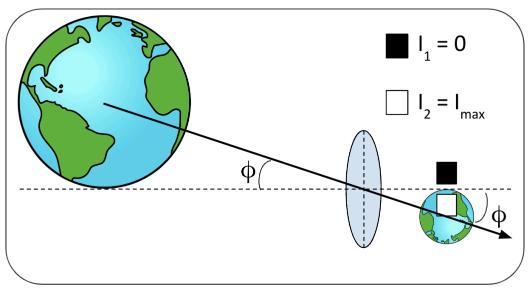


Figure 2: Phi Visualization

Since we are assuming an LEO of 1000km, and the radius of the Earth is approximately 6300km, φ is ~40 degrees in case 1, when we are perfectly facing the horizon.

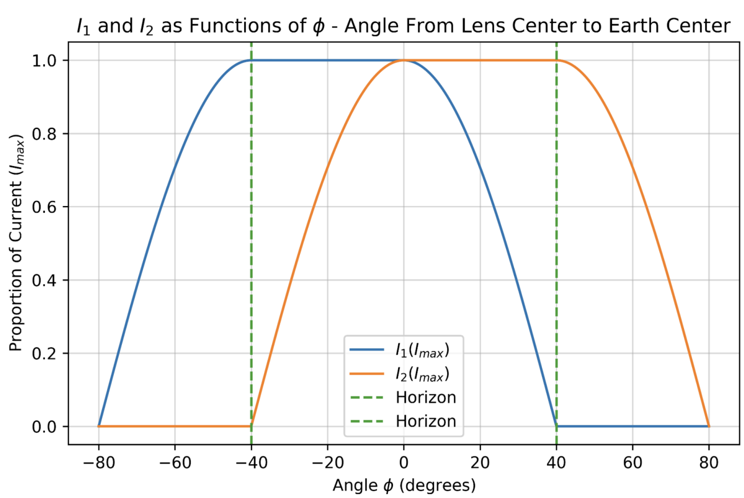


Figure 3: Plotted Current Relationship with Respect to Angle

From the figure above and Table 2 from the appendix, it can be determined that the maximum differential output of currents from both diodes occurs right when the sensor is aligned to the horizon as per the dashed green lines in the figure above (case 1). When the sensor is perfectly misaligned (cases 2 and 3), the differential output is zero. Thus, we know that we are perfectly aligned when the differential output is at its maximum value.

System Specifications

We concluded our project with the following specifications. Note there are two photodiodes each made up of 16 unique elements, each 7.5 µm by 7.5 µm due to maximum diode size constraints in Cadence, and the table below shows the specifications for each photodiode.

Photodiode Dimensions	16 x 7.5µm x 7.5µm = 9×10^{-10} m^2
Current Mirror Gain	I_{out} / I_{in} = 15
Gain @ Max Differential Current	34.2 dB (51.5)
$Power_{max}$, $Power_{min}$	2.43mW, 2.38 mW
Max Differential Voltage Output	1.51V
Ibias, Vdd	15µA, 3.3V
MOSFET Finger Width, Length, Fingers (N)	120nm (default), 45nm (default), 15
Lens Parameters assuming LEO, assuming 1x magnification	Diameter: 60um Distance from sensor: 70um
IC Layout Footprint	69 µm x 69 µm
Minimum Sensor Footprint (including optics)	~ 70 µm x 70 µm x 70 µm

Table 3: Final Circuit Specifications

The active area of the sensor is 60 µm x 60 µm, thus assuming a 1x magnification of the projection of the Earth onto the sensor for simplicity of the lens, the lens needs a minimum diameter of 60 µm. The distance of the lens from the sensor is 70 µm since the angle at which the Earth appears in an LEO orbit is 80° and 60 µm / tan(40°) ~ 70 µm.

Circuit Schematics

Photodiode

This project's central component was photodiodes. How we position the photodiodes and the number of them will determine the rest of the circuit. In order to avoid needing to use linear algebra in our circuit we use a one-dimensional array with two photodiodes whose common centroid is lined with the middle of the lens. We also assume no magnification from the lens.

Because we are in LEO and positioning ourselves to Earth's horizon, the irradiance hitting the photodiode comes from the sun's light rays reflecting off of the Earth back into space.

Defined as the amount of electromagnetic radiation hitting a given surface in terms of watts per square meter, it is almost held constantly at 100 W/m^2 in outer space (1).

We then modeled the photodiode from a real and commercially available photodiode that we thought was best suited for our circuit, [QSB34ZR](). It had a photocurrent specification of 37 µA per every 10 W/m^2. With an irradiance of a hundred and a sensitive area of 2.5 mm x 2.5 mm we get a maximum photogenerated current of 370 µA. Reducing the photodiode area to 30 µm x 30 µm we get a maximum current of 50 nA. This would be the current whenever light is shining directly onto all parts of the photodiode. Intuitively, if no light is shone on the photodiode the photogenerated current would be approximately 0 A.

Realistically, the current going through the photodiode when no light is present is 4 pA, also called dark reverse current. But because the shunt resistance is so high and the dark reverse current is more than 12,000 times less than the maximum current, we approximate this as 0 A. We can then simplify the photodiode model as a PN diode in parallel to an ideal current source representing the photogenerated current as shown in the schematic below.

Current Mirror

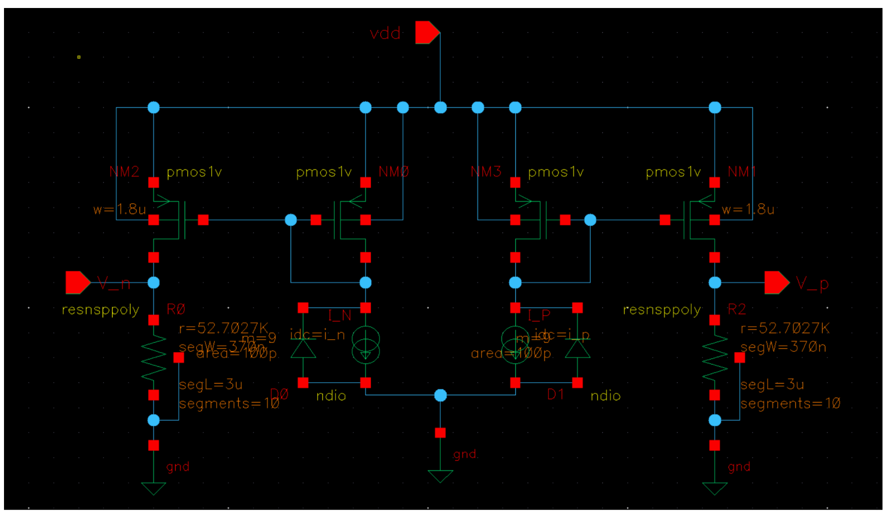


Figure 4: Current Mirror Schematic

The current mirror consists of two photodiodes shown in the middle with a parallel current source, the current mirror MOSFETs, and resistors to convert the amplified current to a voltage that's fed into the differential amplifier. The current mirror was designed to have the following specifications: Vdd = 3.3 V, Current Gain = 15 (23 dB), R = 48.75 kΩ.

The table below shows the DC simulation of the 3 cases specified in the System Design section. The unloaded power draw is very low with a maximum of 11 uW which is ideal for a small satellite.

	Case 1 (Aligned to Horizon)	**Case 2 (Directly Facing Earth)**	**Case 3 (Misaligned to Space)**
Photocurrents	50 nA (max), 0 A	50 nA, 50 nA	0 A, 0 A

(I_p, I_n)	(min)		
Output Voltages (V_p, V_n)	85 mV, 1.8 mV (~ 83 mV difference)	85 mV, 85 mV (0 V difference)	1.8 mV, 1.8 mV (0 V difference)
Total Power	~ 5.5 uW	~ 11 uW	~ 0.22 uW

Table 4: Current Mirror DC Simulation

Differential Amplifier

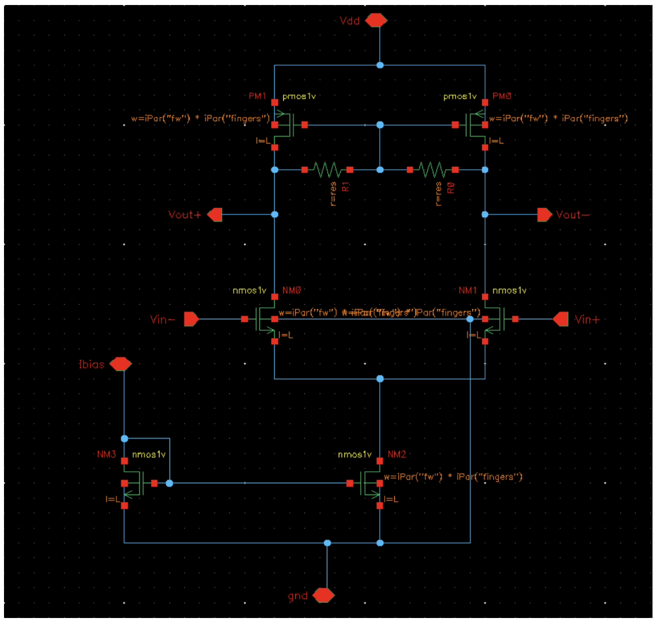


Figure 5: Differential Amplifier Schematic

For our final design, we decided to use two simple OTAs in series for the differential amplifier. We were able to achieve a gain of 24 dB with one OTA. The resistor values of 100 kΩ are used to bias the gates of both PMOS based on the average output voltage.

Complete System Testbench

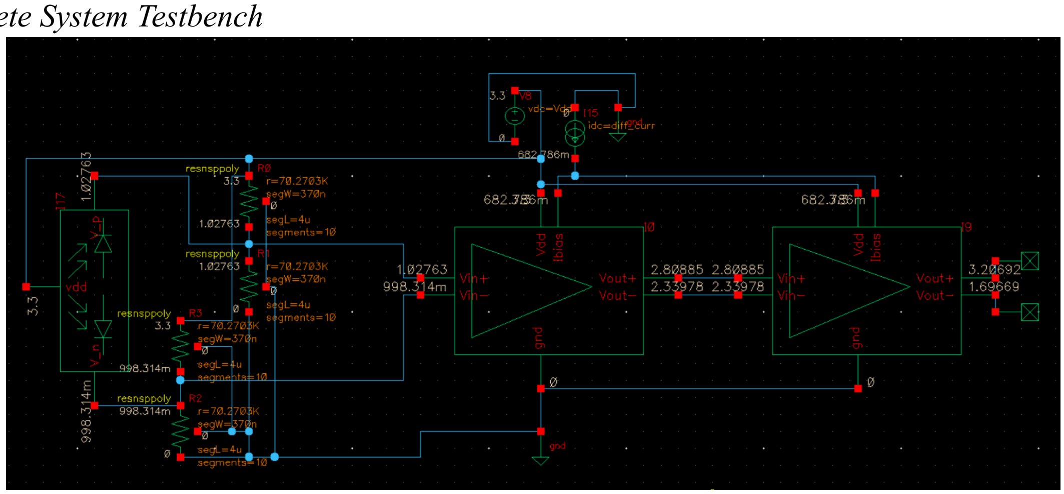


Figure 11: Testbench Setup with Node Voltages Annotated for Max Differential Case

The overall system, from the photodiode input current, modeled by current sources, to the differential output, is shown above. There are two resistor voltage divider networks, with each resistor having a value of 70.3 kΩ that serve the purpose of biasing the output voltage from the photodiode current mirrors to ensure it is within the input range spec of $V_{DD} - V_{OD} > V_{incm} > 2V_{OD} - V_{THn}$. Biasing to approximately 1 V was found to work well and achieve the spec of 1.5 V differential output swing. Such a large load relative to the 50 kΩ used for the current mirror does decrease the current mirror's effectiveness, yet this reduces the size of the layout and the gain of both differential stages is still sufficient to meet the 1.5 V spec.

	Case 1 (Aligned to Horizon)	**Case 2 (Directly Facing Earth)**	**Case 3 (Misaligned to Space)**
Photocurrents (i_p, i_n)	50 nA (max), 0 A (min)	50 nA, 50 nA	0 A, 0 A
Diff Amp Output Voltage	3.21 V, 1.70 V (1.51 V difference)	2.50 V, 2.50 V (0 V difference)	2.50 V, 2.50 V (0 V difference)
System Total Power	~ 2.38 mW	~ 2.43 mW	~ 2.40 mW

Table 5: Differential Amplifier DC Simulation

Please see Table 3 for more details on the final testbench specifications for the entire system.

Cadence Simulations

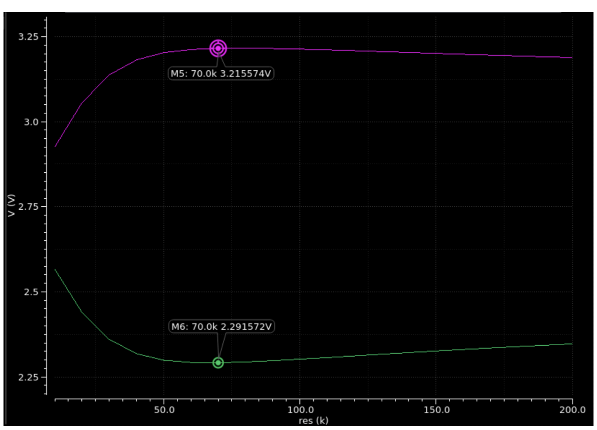
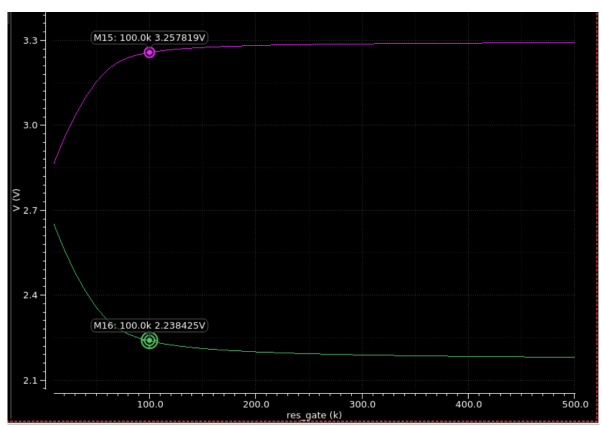
Figure 6: Biasing Resistors Effect on Differential Voltage Output Range	**Figure 7: Effect of Differential Amplifier Gate Resistance on Gain**
	

Figure 6 was used to determine the optimal value of the biasing resistors for maximum differential output voltage. 70 kΩ was determined to be the ideal value as it maximizes that output range. Figure 7 above shows the effect of the differential amp's gate bias resistance on the output voltage range. To maximize the range and minimize the layout area, 100 kΩ was used.

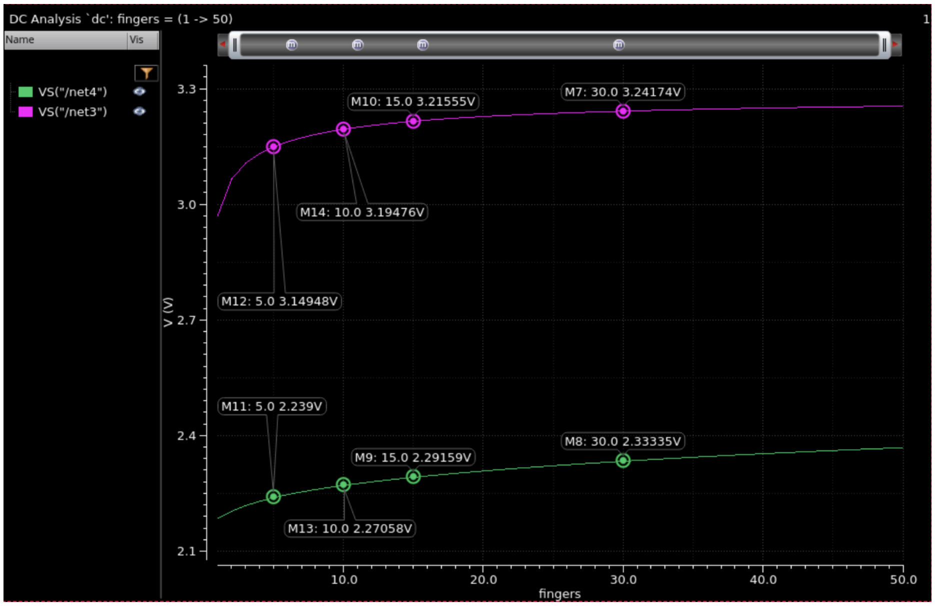


Figure 8: Effect of Number of Fingers on Differential Output

This figure shows a sweep over N, the number of fingers in the transistors for the differential amplifier stages. N = 15 was used as the value as this maximized the output range.

Figure 9: Differential Output (V) vs Photodiode Current (i_p increases to 50 nA, i_n = 0)

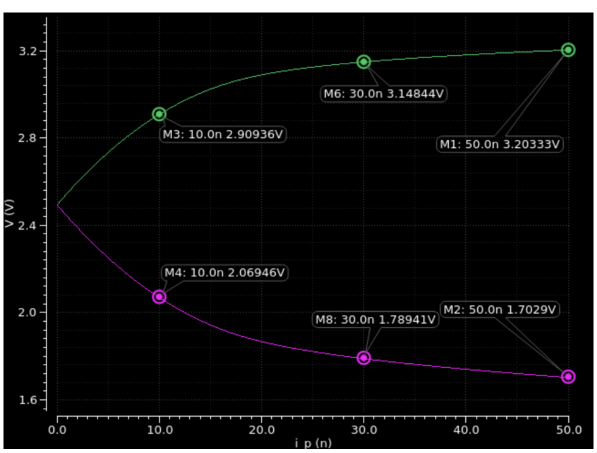


Figure 10: Differential Output (V) vs Photodiode Current (i_p increases to 50 nA, i_n = 50 nA)

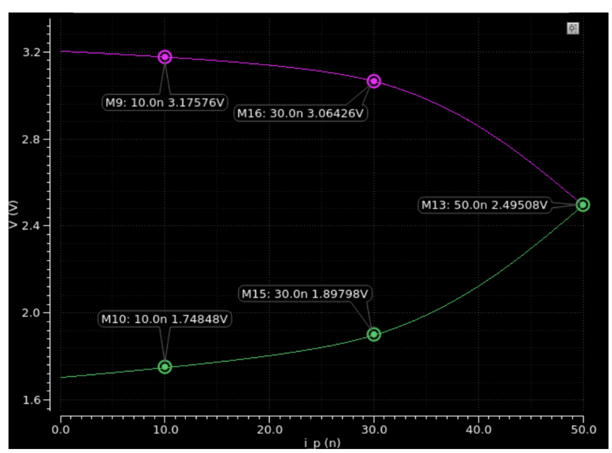


Figure 9 above shows the case of going from space, where there is no current on either diode to perfectly facing the horizon, where there is 50 nA of i_p and 0 of i_n.

For Figure 9, a sweep was performed over the output current of one of the photodiodes, from 0 to 50 nA while keeping the other at 0. We can see that the pattern is non-linear as the devices are likely out of saturation above a range of about 15 nA. In hindsight, it would have been better to optimize for the linearity of the differential voltage across the whole range of currents as opposed to the amplitude of the differential output. For future iterations of this horizon sensor, a way to resolve this would be to either decrease the photocurrent by reducing their respective area or reduce the gain of the differential amplifier by using a single stage instead of two stages as in the current design. Specifically, the area could be reduced by a factor of 5 to have 10 nA be the maximum output current as this range of the plot is still very linear as shown above.

Figure 10 above shows the case of going from being perfectly aligned at the horizon to directly facing the Earth. As discussed with Figure 9, the differential output is not linear in this case either.

Layout

In the figure below, the upper rectangle of diodes is the first photodiode, and the bottom rectangle is the second photodiode. The 16 diodes within each photodiode are connected in parallel. 16 diodes of 7.5 µm by 7.5 µm active area were used for each photodiode as they can easily be laid out in a 4x4 grid and output enough current (50 nA) to achieve the desired differential output (1.5V). 10 µm x 10 µm diodes would have resulted in an equivalent area 3x3 grid but gave errors when laying out in Cadence.

While it is important to have the spacing between the diodes at a minimum for maximum angular resolution of the sensor, the closest that Metal 1 layers can be in Cadence without throwing errors is 1.25 µm. Thus, 1.25 µm was used as the distance in the middle between the diodes. A benefit of this result is that the sensor is not sensitive to small perturbations in the orientation of the satellite relative to the horizon, but has a built-in dead zone of horizon alignment just under 2° to prevent over-compensation by the feedback mechanism. This minimum spacing is also the reason why the ground and photodiode output traces were not routed in between the diodes, but rather on the outside.

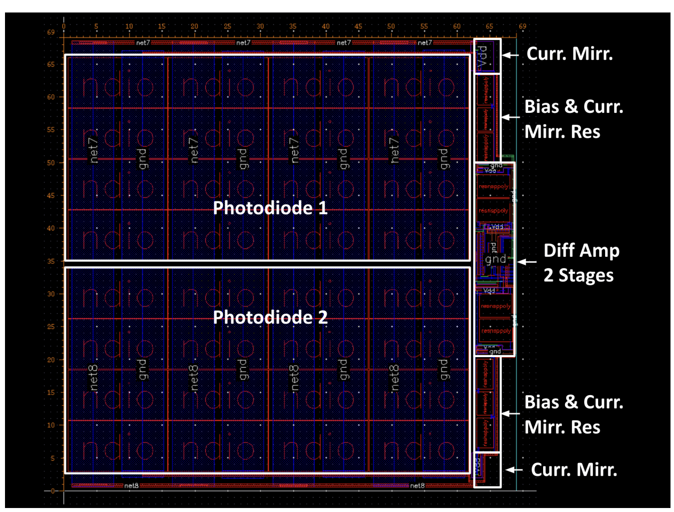


Figure 14: Zoomed Out View of Layout with Component Annotations

The photodiode current mirror and diff amp layouts (Figures 15 and 16 from the appendix, respectively) are shown in the figure above. Note the NWell is tapped to the ground trace, as is the case for all the other NMOS to pass LVS.
It is important to note that the layout only uses 3 layers in total. To name a few benefits of this low layer count, this is good from the perspective of cost as fewer masks are required than with more layers, and the overall manufacturing process is simpler.

Different trace widths were used to minimize resistive losses as in the table below. In particular, thicker widths compared to the default 0.6um were used for the pins interfacing with the IC and the outputs of the first and second photodiode as they carry more current and trace over greater distances, respectively. The widths are documented in Table 6 in the appendix.

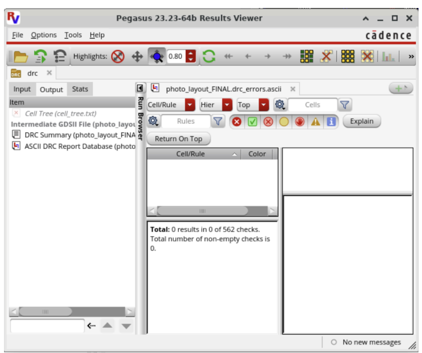
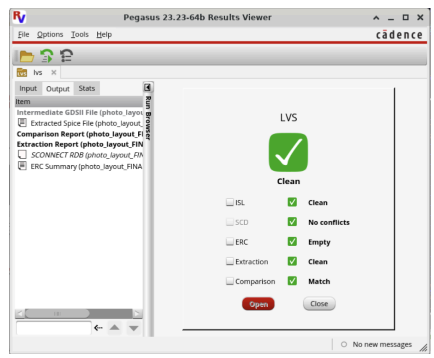
DRC passing ✅	LVS passing ✅
	

Table 7: Layout Passes DRC and LVS

Challenges & Lessons Learned

While designing the horizon sensor we faced multiple challenges. First while figuring out the system there were multiple assumptions we had to make to simplify our design which was not simple to determine at first. There were various pieces to the system to consider such as the photodiode current, optical physics, satellite orientation, current and differential amplification, and actuator control. It helped to draw a block diagram, brainstorm multiple ideas, and choose the best solutions although this took several iterations.

In our first iteration, we referenced Lab 3 for the differential amplifier as it provided a high gain, however, the circuit's complexity was unnecessary for our purposes. In the final iteration we simplified the differential amplifier to two simple OTAs in series providing a gain of at maximum differential photodiode current. This reduced the max power consumption by a factor of 16 relative to our first iteration (40 mW vs 2.43 mW). In the first iteration, we also based our photodiode dimensions and photocurrent on the [QSB34ZR photodiode]() which is about 2.5 mm x 2.5 mm in area producing a max current of 370 µA (2). This would require us to layout a total of over 100,000 unit 7.5 µm x 7.5 µm diodes (very time consuming) so we decided to shrink the area of the photodiode to be 30 µm x 30 µm made up of 16 unique diodes each 7.5 µm x 7.5 µm. While these photodiodes produce a smaller max current of 50 nA, we increased the resistor on the current mirror to ~50 kΩ to provide a reasonable voltage to be amplified by the differential amplifier. Overall, we learned a significant amount from this project. One of the most important lessons we learned was to keep the design as simple as possible avoiding unnecessary circuits that can increase the power consumption.

Works Cited

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3. T. Nguyen, "Attitude Determination Using Infrared Earth Horizon Sensors," Journal of Spacecraft and Rockets, vol. 52, no. 4, pp. 1035-1046, 2015.
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5. "The Physical Operation of Light-Sensitive pn Junctions," All About Circuits. [Online]. Available: https://www.allaboutcircuits.com/technical-articles/the-physical-operation-of-light-sensitive-pn-junctions/. [Accessed: Oct. 25, 2024].
6. T. Nguyen, "Attitude Determination Using Infrared Earth Horizon Sensors," in 28th Annual AIAA/USU Conference on Small Satellites, Logan, UT, 2014.
7. S. Mobasser and C. C. Liebe, "Earth horizon sensor for attitude determination of LEO satellites," in 2008 IEEE Aerospace Conference, Big Sky, MT, 2008, pp. 1-8.
8. "Radiation," NOAA Global Monitoring Laboratory. [Online]. Available: https://gml.noaa.gov/grad/about/rad.html. [Accessed: Oct. 25, 2024].

Appendix

Angle φ	I_1 (Top Photodiode)	I_2 (Bottom Photodiode)
80 > φ > -80	0	0
-80 < φ < -40	$I_{max}\sin(2.25\varphi)$	0
0 < φ < -40	I_{max}	$I_{max}\cos(2.25\varphi)$
40 < φ < 0	$I_{max}\cos(2.25\varphi)$	I_{max}
80 < φ < 40	0	$I_{max}\sin(2.25\varphi)$

Table 2: Current Relationship with Respect to Angle

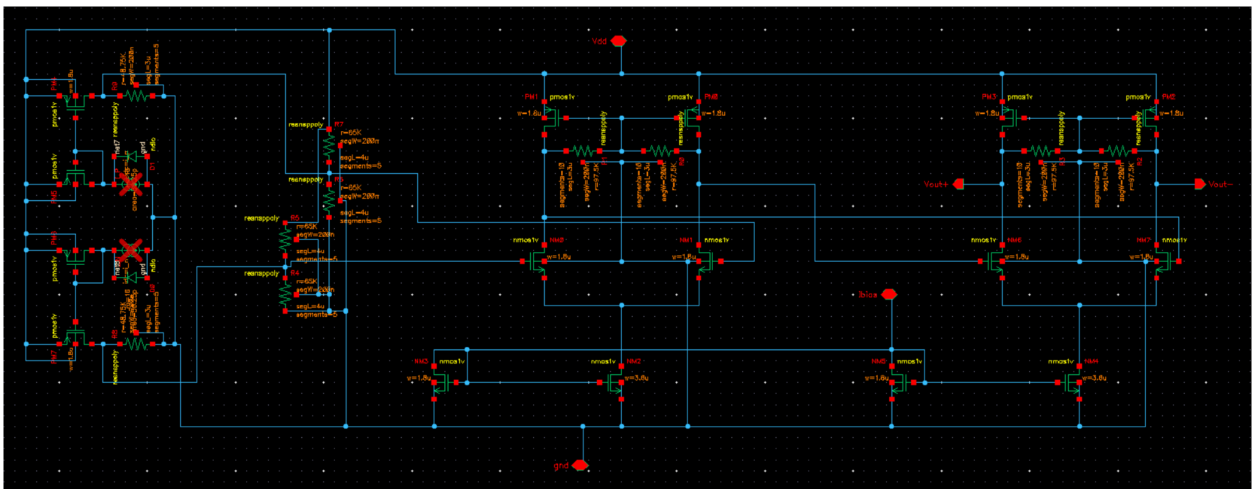

Figure 12: Combined Circuit for Layout

Components were extracted from the testbench to create the schematic above for layout.

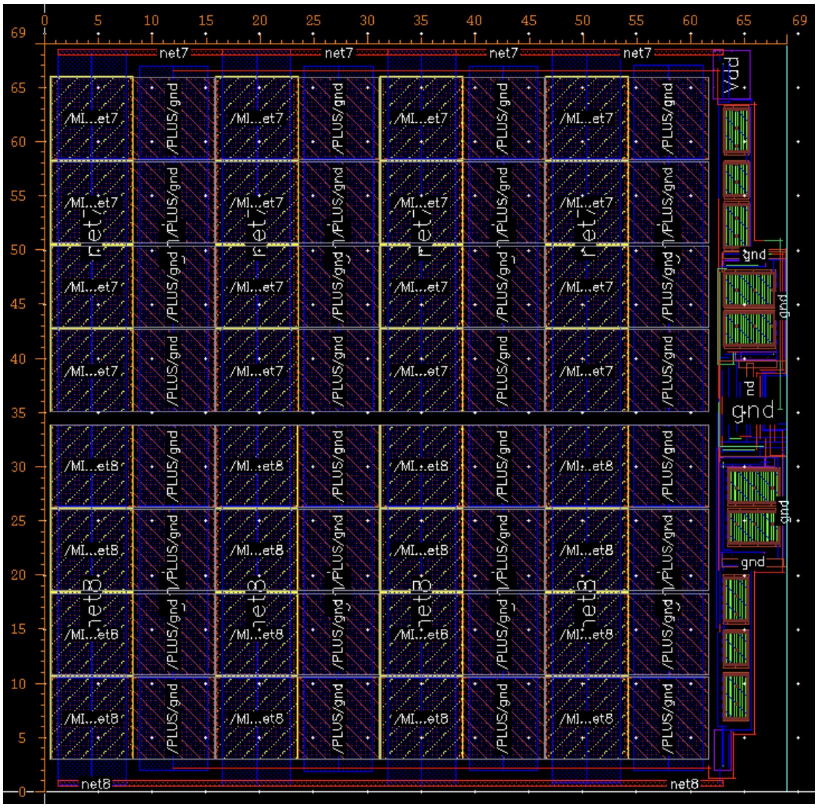

Figure 13: Zoomed Out View of Layout with Layer Shading. Note ruler is in um

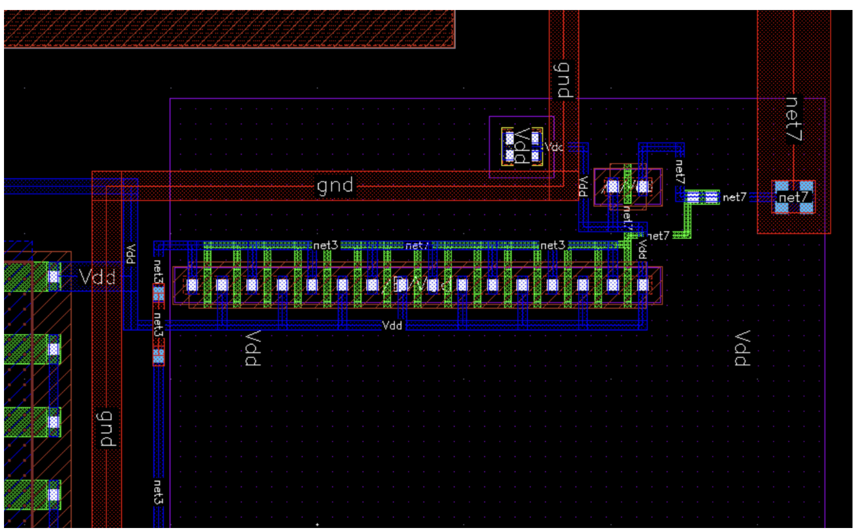

Figure 15: Photodiode Current Mirror (rotated CW by 90°)

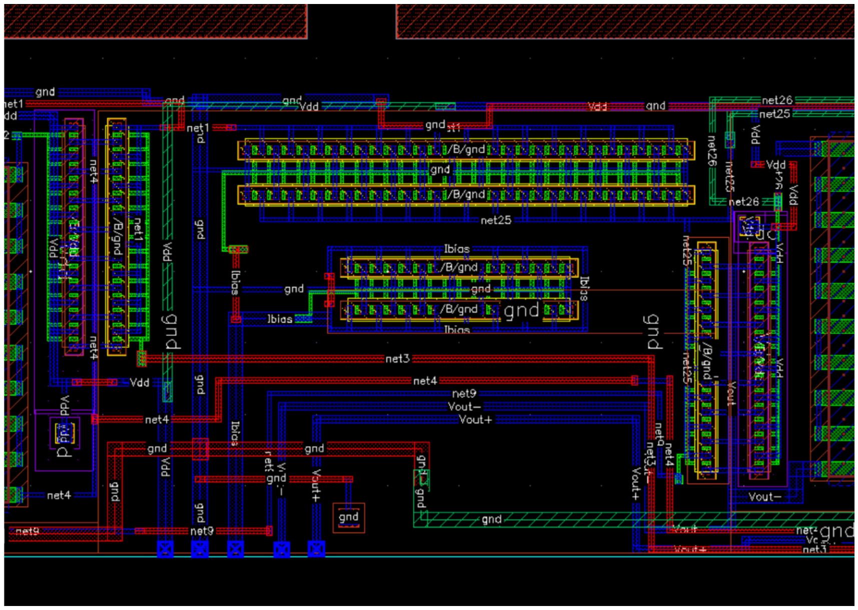

Figure 16: Diff Amp Components and Pins (rotated CW by 90°)

Nets	**Width**
Photodiode 1 & 2 Output	0.5µm
Output Pins: Vdd, gnd, Ibias	0.2µm
Output Pins: Vout-, Vout+	0.1µm
Other Metal 2	0.08µm (default)
Other Metal 3	0.08µm (default)
Other Metal 1	0.06µm (default)

Table 6: Typical Net Trace Width

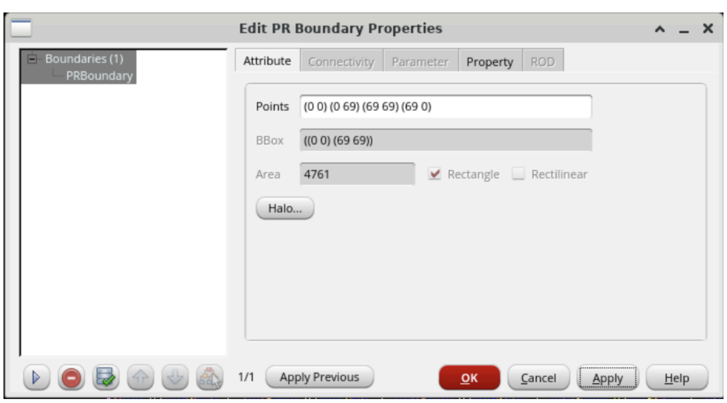

Figure 17: PR Boundary Dimensions are 69um x 69um