Atom Interferometer Gravity Gradiometer (AIGG) Instrument Technology Development Readiness, Flight Implementation, and Expected Performance

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Note: This version denoted "_NEC", or No Export Control, has specific sub-figures containing instrument details redacted to eliminate the need for Export Control. The original version (without the NEC) contains the sub-figures with an Export Control banner.

Abstract: The 2017 ESAS Decadal Survey notes "Achieving spatial scales of 100–200 km and an accuracy of <1 cm water equivalent RMS would require additional GRACE-FO satellite pairs and/or new technology such as an advanced gravity gradiometer." The candidate measurement for the Mass Change Designated Observable in the 2017 ESAS is the "Measurement of gravity anomaly with spatial resolution of 200 km at the equator." Simulation studies have demonstrated that an advanced Atomic Interferometer Gravity Gradiometer (AIGG) provides a technological pathway to meeting the 2017 ESAS Decadal Survey goals. The AIGG uses spatial fringes of the atom clouds to measure and separate out the rotational forces enabling a single axis instrument implementation. A single spacecraft utilizing the AIGG technology can observe TVG to the required levels. The MCDO study has noted the high science value from this technology implementation, and in particular has found:

- A single-satellite AIGG architecture significantly outperforms the 2-satellite in-line satellite-to-satellite tracking (SST) configuration with improved Laser Ranging Interferometer (LRI) and accelerometer technologies.
- A single-satellite AIGG achieves similar performance as the 2-satellite SST pendulum and 3-satellite in-line plus pendulum architectures.
- A single-satellite AIGG is near the performance of a 4-satellite Bender SST architecture.

This manuscript describes the AIGG instrument technology and summarizes the current state of a laboratory prototype AIGG instrument achieving TRL-4 in the Fall of 2021. The laboratory instrument is a prototype for a full 10 μE sensitive flight instrument capable of a factor of 7 improvement in monthly gravity field recovery over GRACE and GRACE-FO from a single satellite. The sensitivity is per shot with a 30 second observation rate for a single interferometer beam, and 10 second observation rate for a three beam interleaved instrument. An Instrument Design Laboratory (IDL) study for a full sensitivity instrument is summarized providing design and implementation details, current TRL assessment, and remaining technical challenges. We assume that this AIGG instrument would initially be implemented as a technology demonstration and then could later be implemented in a full science mission to take advantage of the instrument's ultimate measurement performance. We therefore present AIGG's performance under both implementation scenarios. The technology demonstration instrument would have an interferometer length scale of 0.66 m and a sensitivity of 75 μE (per shot with a 20 second observation rate) capable of monthly gravity field recovery at the same performance as GRACE. Development of this instrument to TRL-6 for incorporation as a technology demonstration mission would require a ~4 year effort. A summary of the Mission Design Laboratory (MDL) study for the technology demonstration mission is provided.

1. Technology Benefits to Earth Science and Technology Description

1.1 Technology Alignment and Benefits to Earth Science

The time-variable gravity (TVG) measurements provided by the Gravity Recovery and Climate Experiment (GRACE) have revolutionized our understanding of many important geophysical processes, including Earth's land ice mass evolution, hydrology mass storage and transport, eustatic ocean variability, and solid Earth processes such as earthquakes and glacial isostatic adjustment [1,2,3,4]. The 2007 Earth Science Decadal Survey recognized the far-reaching benefits of continuing the TVG observation record and recommended the GRACE Follow-On (GRACE-FO) mission, which launched in May 2018. More recently the 2017 Decadal Survey for Earth Science and Applications from Space (ESAS) has recommended a gravity mission as one of the four primary designated observable missions; referred to as the Mass Change Designated Observable (MCDO) mission [5]. Space-borne TVG measurements are truly unique, and directly address three of the Earth System Science themes of the 2017 ESAS Decadal Survey: (1) Global Hydrological Cycle and Water Resources; (2) Climate Variability and Change: Seasonal to Centennial; and (3) Earth Surface and Interior: Dynamics and Hazards. These themes clearly define the compelling science and societal needs for continuing the TVG observation record beyond GRACE-FO, and for pursuing technologies to improve the accuracy, temporal, and spatial resolution of current TVG measurements.

The more recent 2017 ESAS Decadal Survey references the 2015 study, *Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society*, which was developed under the auspices of the International Union of Geodesy and Geophysics (IUGG) and jointly with the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG). This study outlines the need for a dedicated gravity observational system, its science and societal benefits, and the specific observational requirements for a Next Generation Gravity Mission (NGGM) [6]. The 2017 ESAS Decadal Survey references the NGGM study noting that "to make significant improvements that would advance studies of earthquakes, glacial isostatic adjustment, and glacier-scale processes would require constellations of gravity satellites, development of new gradiometer technology, or both [5,6]." Furthermore, the 2017 ESAS Decadal Survey notes: "Achieving spatial scales of 100–200 km and an accuracy of <1 cm water equivalent RMS would require additional GRACE-Follow-On satellite pairs and/or new technology such as an advanced gravity gradiometer." Simulation studies have demonstrated that an advanced Atomic Interferometer Gravity Gradiometer (AIGG) provides a technological pathway to meeting the 2017 ESAS Decadal Survey and 2015 NGGM performance targets [7,8].

Gradiometer-based missions directly measure gravity gradients using pairs of accelerometers along baselines housed in a single satellite. Because the baselines are short and the sensitivity of these instruments is limited, earlier gradiometers like that on GOCE were not able to capture the monthly TVG variability. The accumulation of multiple months of observations was required to sufficiently reduce the noise for measuring the static and long-period gravity signals. Atomic-interferometry-based gradiometers will have significantly increased sensitivity enabling observation of the long- and short-wavelength portion of the TVG at monthly and higher temporal resolution. It should also be noted that gradiometers measure rotational forces in addition to gravitational forces that must be separated. The AIGG uses spatial fringes of the atom clouds to measure and separate the rotational forces enabling a single axis instrument implementation.

Recently the MCDO study has simulated and quantified the expected performance of a single satellite gravity gradiometer with 2 m radial baseline and three interleaved interferometry beams; concluding that:

- A single-satellite AIGG architecture significantly outperforms the 2-satellite in-line satellite-to-satellite tracking (SST) configuration with improved Laser Ranging Interferometer (LRI) and accelerometer technologies.
- A single-satellite AIGG achieves similar performance as the 2-satellite SST pendulum and 3-satellite in-line plus pendulum architectures.
- A single-satellite AIGG is near the performance of a 4-satellite Bender SST architecture.

The ability to advance TVG observations from a single satellite could potentially reduce the cost relative to SST multi-satellite implementations and provides flexibility in the implementation of a constellation of AIGG and SST missions to mitigate temporal aliasing and advance temporal and spatial resolution.

1.2 Atom Interferometer Gravity Gradiometer (AIGG) Concept

The AIGG instrument consists of two gravimeters each with its own atom cloud and separated by a baseline length, L (Figure 1). The gravimeters use atom interferometry and the wavelike properties of atoms to measure gravitational acceleration. Each gravimeter uses successive laser beam pulses to interact with atoms and then measures the atom's inertial trajectory with respect to an optical reference mirror fixed relative to the sensor structure; thereby laser-ranging the distance between the atoms and the instrument. The laser beam frequencies drive a transition between two quantum states of the atom (Figure 1). The atom records the phase of the driving electromagnetic field during each resonant interaction. This phase is directly proportional to the distance the atom has traveled between the pulses. Thus, the lasers act as a high precision ruler by which the atom's trajectory is measured by each gravimeter.

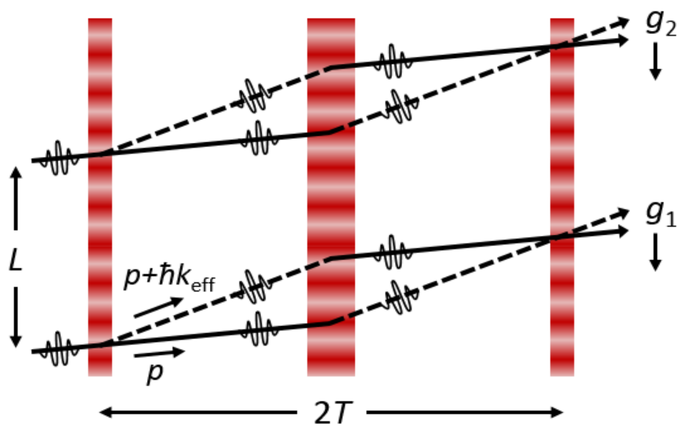


Figure 1: Gravity gradiometer concept. The spacetime diagram for a gravity gradiometer comprises two LPAI gravimeters separated by baseline L. The 1st laser pulse puts each atom wave packet into a superposition of two different momentum states. Over time T this momentum difference yields a spatial superposition with a wave packet separation of ~50 cm. The 2nd pulse reverses the momentum of the two states and the 3rd pulse recombines them, yielding an interference pattern that is sensitive to the local gravitational acceleration g.

The gravity gradient measurement is of significant benefit as it provides for the cancellation of many common gravimeter error sources. The sensed gravity gradient vector, T_{ii}, is parallel to the line that connects the two atom clouds and is the difference in acceleration output of the two atom clouds divided by the baseline. The atom clouds sense acceleration due to the gravity gradient and the rotational forces. The quantity measured by the gravity gradiometer in the presence of gravity gradients and rotational forces in the z-axis direction is then:

$$\Gamma_{zz}(t_0) = \frac{1}{L\,T^2}\left(-\int_{t_0}^{t_0+T} dt' \int_{t_0}^{t'} (a_1(t) - a_2(t))dt + \int_{t_0+T}^{t_0+2T} dt' \int_{t_0}^{t'} (a_1(t) - a_2(t))dt\right)$$

where a_1 and a_2 are the local values of acceleration at the locations of the two atom cloud accelerometers. It should be noted that the observation sampling interval contributes to the resolution of gravity signal and this is properly modeled in the simulations to be discussed. The gravity gradient is isolated from rotational forces using sensor-unique rotational compensation, in combination with conventional satellite guidance, navigation and control. Rotation of the interferometer beams between interferometer pulses relative to an inertial frame causes a phase shift across the atom cloud. A CCD camera can measure the resulting spatial fringe pattern. Distinct features of a single-shot image of this spatial fringe pattern determine the interferometer rotation and fringe contrast. An independent measurement of AIGG platform rotation can control interferometer beam mirror tilts to compensate for the rotation [9].

1.3 AIGG Instrument Description

Goddard Space Flight Center and AOSense have collaborated over the past 7 years to develop an AIGG laboratory demonstration instrument [8]. The initial instrument development was funded by the Earth Science Technology Office (ESTO), Instrument Incubator Program (IIP). The AIGG instrument is a high-performance, single-tensor-component gravity gradiometer applicable to Earth science studies in low-Earth orbit. The design employs light-pulse atom interferometry using cold atoms (meaning atoms with very low velocity spread), and implements recent developments in atom cooling, interferometry, and detection technologies [10]. The laboratory gravity gradiometer instrument serves as a prototype to design and develop a space flight instrument. The laboratory instrument is targeting a sensitivity of < 1 Eötvös /Hz$^{1/2}$ in the terrestrial environment (interrogation time T = 300ms, Large Momentum Transfer (LMT) of 12ħk, atom cloud size of 10^6 atoms, baseline L = 2 m). An Eötvös (E) is the unit of gravity gradient, where 1 Eötvös (E) is 10^{-9}/s^2. The laboratory instrument is being used to design and develop a future gradiometer adapted for space operation that will capitalize on the long interrogation times that a microgravity environment enables. Ultimately, such a sensor would achieve a gravity gradient precision

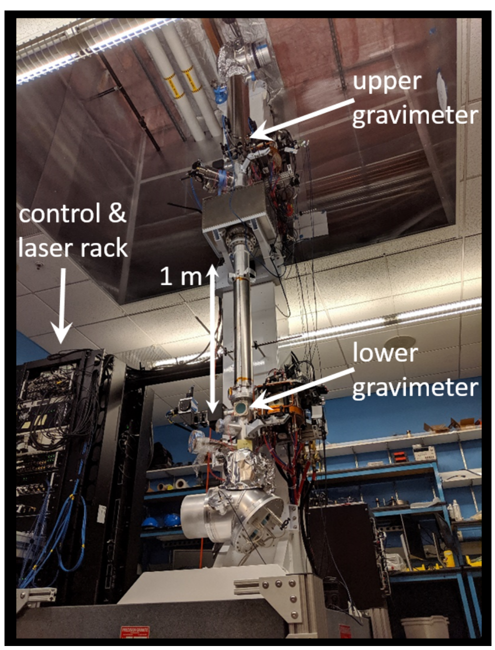


Figure 2. Atom interferometer gravity gradiometer (AIGG) instrument.

of ~10^{-5} E/shot, or 10 μE, with interrogation times, T=15s, a 2 m baseline, and a 0.033 Hz measurement rate for a single interferometer beam. This sensitivity corresponds to a short-term noise floor of 5.5×10^{-5} E/Hz$^{1/2}$. A similar instrument employing three interleaved interferometer beams would have a 0.1 Hz data rate and a 3.2×10^{-5} E/Hz$^{1/2}$ noise floor.

1.4 AIGG Laboratory Instrument Operation and Status

The AIGG Laboratory instrument is fully assembled and is currently being tuned and optimized to produce laboratory observations of the gravity gradient in the terrestrial environment (Figure 2) [8]. Presently, the AIGG has generated ultra-cold atom clouds for two gravimeters and has achieved the first gravity gradiometer signals from two gravimeters (Figure 3).

The AIGG instrument measurement process is outlined in Figure 4. The remainder of the section describes and demonstrates the laboratory instrument's operational processes used to generate atom clouds and measure their accelerations under gravity.

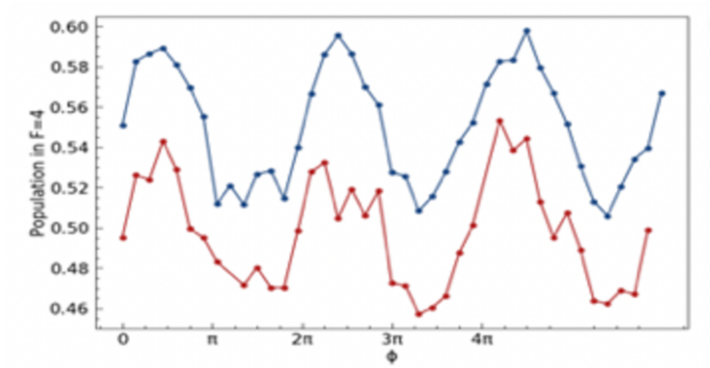


Figure 3. Fringes from the two AIGG gravimeters. Differencing the two gravimeter measurements yields the gravity gradient.

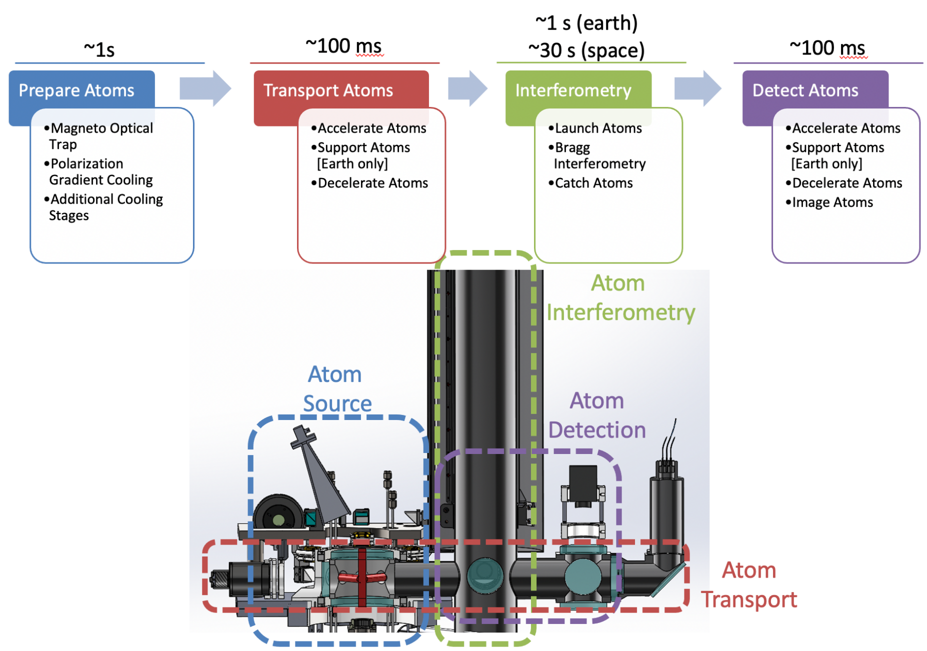


Figure 4. AIGG Instrument Measurement Process

Prepare Atoms

The measurement process starts with the generation of the atoms. Two identical atom sources deliver ultracold atom clouds to the two AIGG gravimeters. A two-dimensional (2D) magneto-optical trap (2D MOT) cools and transversely traps cesium atoms exiting a cesium reservoir (Figure 5(a)). The 2D MOT directs the atomic beam toward a 3D MOT (Figure 5(b)), which traps and further cools the atoms (Figure 5(c)). As the 3D MOT releases the atoms, polarization-gradient cooling (PGC) cools the atoms to ~10 μK.

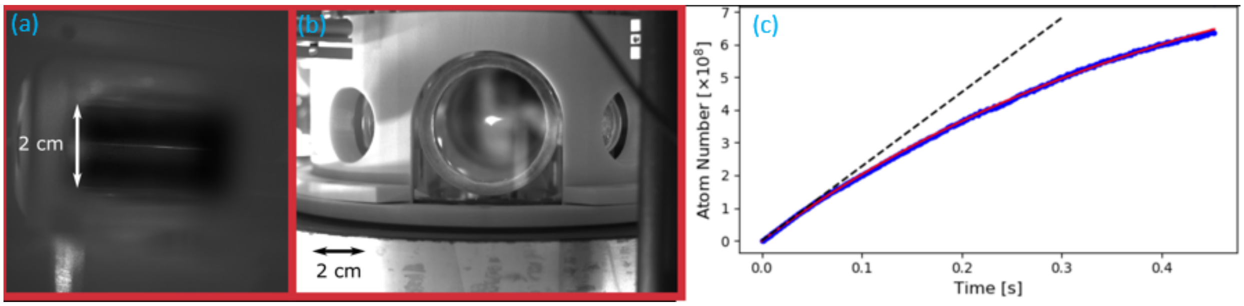


Figure 5. Magneto-optic trap (MOT) atom sources for the AIGG.
(a) Gravimeter 2D MOT. The thin horizontal bright line at the center of the image is resonant fluorescence from the cesium atomic beam. **(b)** Gravimeter 3D MOT. The bright spot in the center of the window is a trapped cesium cloud. **(c)** Atom loading curve for the 3D MOT, showing the number of atoms trapped in the MOT as a function of the loading time; an exponential fit indicates that the MOT loads *N* = 6×10^8 atoms at a rate *α* = 1×10^9 atoms/s over 500 ms.

Next, additional cooling stages further cool the atoms to ~50 nK. In space, these cooling stages can reach ~3 nK. After reaching this target temperature, a sequence of microwave pulses transfers the atoms into a magnetic-field-insensitive state in preparation for atom interferometric gravimetry.

Transport Atoms

Next the cold atoms are shuttled from cooling chamber to interferometry chamber over 20 cm. An off-resonant optical lattice transports atoms from the cooling stage to the interferometry region without degrading the ultracold cloud temperature. Optical lattices are generated by counter propagating lasers in three dimensions. A changing frequency of either of the pairs results in a traveling standing wave that moves the atoms. Figure 6 demonstrates precision atomic positioning by the AIGG lattice lasers.

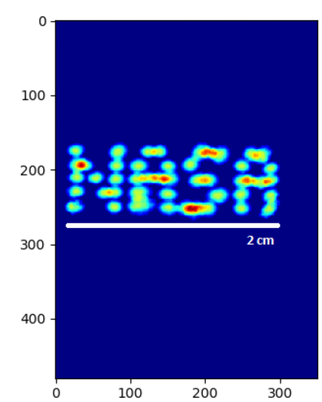


Figure 6. Lattice shuttling in AIGG. This composite image depicts precision lattice shuttling of the atom cloud to 47 distinct positions [*x and y axis values represent camera pixels*]

Interferometry

After shuttling, lattice lasers will launch the atoms vertically upward to maximize the available interferometry time on Earth. During this vertical trajectory, a single set of interferometer laser pulses generates the gravimeter signals for both the upper and lower interferometers. A CCD camera detects resonance fluorescence from each atomic state for each atom cloud.

Detect Atoms

Figure 7 shows the first atom fringes in the lower gravimeter of AIGG. The interferometer that generated these fringes had a short interrogation time, T, which is the time between consecutive interferometer pulses, as depicted in Figure 1. This time interval is the time between turning off the shuttling lattice and the time for the falling atoms to cross the vacuum chamber window. This is a very short time interval but demonstrates the coherence in the interferometer and verifies the functionality of the interferometer lasers and their drive electronics. Launching the atoms vertically upward enables T to increase, yielding higher sensitivity. The fringe phase noise results from platform vibrations, which will cancel out as a common-mode noise for the gradiometer signal.

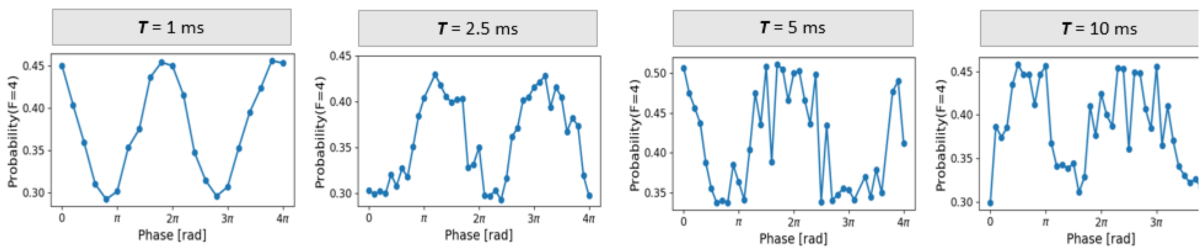


Figure 7. First gravimeter signals from lower AIGG gravimeter. Atom interference fringes for varying interrogation time (*T*). Longer interrogation times enable higher sensitivity, both to gravity signals and to platform vibrations but this vibration will cancel out by subtraction of the measured phases in upper and lower gravimeters. Probability on the y-axis is the ratio of the number of excited atoms to the total number of atoms at the start of the interferometry. The phase of the last pulse is changed to trace the fringes.

With the recent acquisition of fringe measurements from the upper and lower gravimeters, AOSense is in the process of completing instrument tuning and optimization to achieve the target laboratory instrument gravity gradient observation sensitivity of < 1 Eötvös /$Hz^{1/2}$.

2. Spaceflight Implementation Considerations and Performance

2.1 Interrogation Time and Baseline Length

The main driver for improved sensitivity of the AIGG in microgravity is the increased interrogation time, along with improvements in detection SNR and atom throughput. The single-shot gravity gradient sensitivity scales as T^2, where T is the sensor interrogation time, and by baseline length L. The full sensitivity flight instrument targets T = 15 s in space. Additionally, the long interrogation time in microgravity requires cooling the atoms to ~3 nK to keep them within the laser beam width during the measurement. The laboratory instrument serves as a prototype for the most sensitive instrument that is technically feasible to implement as a free flyer. The full sensitivity flight instrument targets a 10 μE /shot performance. This requires a baseline of 2 m and an interrogation time of 15 s with a resultant sampling rate of 0.033 Hz for a single beam instrument. The AIGG uses spatial fringes of the atom clouds to measure and separate out the rotational forces enabling a single axis instrument implementation [9]. The 15 s interrogation time produces wave packet separations on the order of 50 cm at each gravimeter [11].

In addition to directly determining the instrument sensitivity, both interrogation time (due to the wave packet separation length needed), and instrument baseline length, dictate the size of the instrument along the interferometry direction which is the largest dimension. Due to engineering considerations, a full packaging of the instrument gravimeter heads within the baseline length of 2 m is quite difficult. A recent Goddard Space Flight Center (GSFC) Instrument Design Laboratory (IDL) Study determined the prototype instrument can be repackaged to a 3.4 m length.

2.2 Gradient Measurement Direction

In addition to interrogation time, T, and baseline length, L, which dictate the instrument sensitivity and size, the direction of the gradient measurement has significant implications on the gravity gradient observation Signal to Noise Ratio (SNR). Measuring the gradient in the radial direction (ZZ) provides the best SNR and is the optimal orientation of a single axis gradiometer for observing TVG. In the radial orientation the instrument will experience a full rotation about an axis perpendicular to the interferometer beam once every orbit revolution. Over the long interrogation times the relative position of the atoms within the interferometry beam will then change as the atoms are in free-fall and the instrument is rotating. This motion could preclude the instrument from closing the interferometry as the atoms move too far out of the laser beams. If this were the only consideration, orienting the instrument to measure the cross-track direction (YY) would potentially solve this issue as the rotation would be about the interferometer beam axis, and therefore impart no relative motion between the atoms and the laser beam. However, the YY orientation of the instrument results in significantly worse recovery of TVG (see next section for performance analysis).

The resultant performance degradation of the YY instrument orientation may be acceptable given that it does not have the issue of the rotational motion of the instrument laser beam relative to the atoms. However, there are two additional issues that require an engineering solution to maintaining the correct position of the atoms within the interferometry beam. First, as with all highly sensitive and precise spaceflight optical instruments (e.g. ICESat-1, ICESat-2, GEDI), beam alignment mechanisms are required to compensate for launch alignment shifts as well as slow varying thermal-mechanical alignment changes [12]. A spaceflight gravity gradiometer is no exception and will require mechanisms to ensure proper beam alignment and interferometry performance. Second, non-conservative forces, foremost atmospheric drag acting on the spacecraft-instrument will cause translational motion of the free-falling atoms relative to the instrument laser beam orientation. Because of these issues, the instrument will require beam steering mechanisms to ensure closure of the interferometry and full performance. Implementation of the beam steering mechanisms will then compensate for launch alignment shifts, thermomechanical variations, translational and rotational motion. With the implementation of the beam alignment mechanisms the AIGG instrument can then be oriented in the radial direction and benefit from the significant improvement in the performance for the ZZ gravity gradient.

2.3 Expected Performance from a Full Sensitivity 10 μE Instrument

Detailed performance simulations for various implementation cases of the AIGG have been conducted within the MCDO study and are therefore congruent to the MCDO simulation details. The simulations were performed using NASA GSFC's precision orbit determination and geodetic parameter estimation software, GEODYN. The simulations assess the ability of the AIGG to recover TVG relative to GRACE calibrated errors and the truth signal, where the truth we seek to measure is the combined mass variability in the hydrosphere, cryosphere, ocean, and atmosphere. (We note that the GRACE calibrated errors are larger at the lowest degrees than the simulated errors of a GRACE-like mission). The TVG performance is expressed as the spherical harmonic degree variance of gravity errors, providing performance assessment over the spatial spectrum from long to short wavelength gravity signals. Rigorous numerical simulations must account for all major sources of error, which includes the AIGG instrument, orbit position, attitude, and temporal aliasing. Aliasing is caused by the high temporal frequency variability in the true geophysical signals that cannot be sufficiently sampled, and this error source is mitigated with the use of atmosphere and ocean de-aliasing (AOD) products.

Our simulation procedures are consistent with those applied by the MCDO study team for assessing a wide variety of architectures and technologies. The simulated truth signal is defined by the ESA Earth System Model hydrology and land ice, GOT4.8 ocean tides, and the AOD RL05 non-tidal ocean and atmosphere. The nominal signal modeled in the reduction of the simulated observations from which the TVG is estimated is defined by the FES 2004 ocean tides and a perturbed AOD model based on ESA Earth System Model [13]. Note that the hydrology and ice signals are excluded from the nominal model as those are the primary signals we seek to estimate. The dates used in the simulated gravity estimates are Jan 1 – Jan 29, 2006. For all performance simulation results reported in this document, the AIGG instrument is modeled in a 500 km altitude polar orbit.

For the sake of simplifying the discussion, we present throughout this report the factor of improvement for various AIGG scenarios relative to GRACE, which is determined by computing the average ratio of the degree variance values over a specified span of degrees; typically, degrees 4–90. We exclude degrees 2 and 3 from the comparison as GRACE-FO does not recover the degree 2 and 3 zonal terms accurately. These zonal terms are replaced by those determined with satellite laser ranging (SLR) [14]. Low degree estimates from SLR and precise orbit determination methods [15] might have sufficient accuracy to be combined with AIGG to capture the full spectrum of degrees 2–90, but this requires additional study.

We first assess the performance of the flight version of the prototype laboratory instrument: single beam, L = 2 m; T = 15s; 0.033 Hz observation rate; 10 μE sensitivity. The analysis applied a measurement noise spectrum of the sensor that is flat over at least the relevant frequency range for Earth applications (0.3 mHz - 0.03 Hz). The sensor error spectrum was estimated from a Monte Carlo simulation analysis performed by AOSense, which included platform angle jitter, platform attitude misalignment, intrinsic

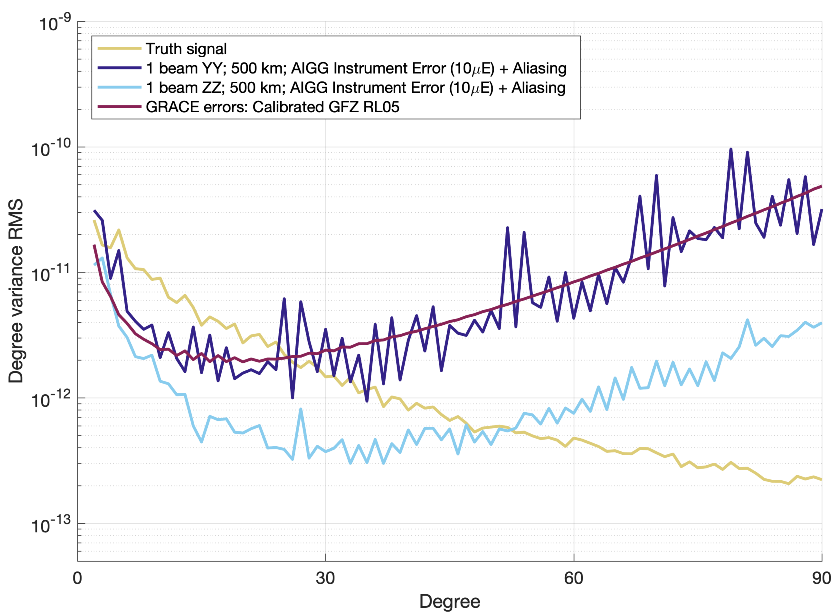


Figure 8. Degree variance of monthly gravity field error spectrums from a 1 beam, 10 μE sensitive AIGG instrument in a 500 km altitude polar orbit; compared with the degree variance of the truth signal (hydrology, cryosphere, tides, non-tidal atmosphere and ocean) and calibrated GRACE monthly gravity fields. The AIGG error spectrums include both instrument error and atmosphere and ocean aliasing. The radial ZZ instrument far outperforms a cross-track YY instrument. The ZZ oriented AIGG instrument represents a factor of 8 improvement over GRACE for degrees 4–90 (factor of 3.5 improvement for degrees 4–30, and factor of 10 improvement for degrees 31–90). *The higher the gravity field degree the smaller the spatial resolution of the gravity signal (e.g., degree 30 = 646 km; degree 60 = 329 km, degree 90 = 220 km).*

random sensor phase noise, Bragg beam static misalignment, atom position fluctuations, and atomic mean velocity fluctuations.

Figure 8 shows the performance of the 10 µE implementation considering errors from instrument noise and atmospheric and ocean aliasing from high frequency mass variation. The YY (cross-track) implementation performs at the same level as GRACE for degrees 4–90. **Orienting the instrument to measure the ZZ rather than the YY provides for a factor of 8 improvement over GRACE (degrees 4–90), and an order of magnitude improvement for degrees 31–90 (646 km to 220 km). Given that the beam steering mechanisms are necessary to address post-launch and long-term thermomechanical alignment shifts, the ZZ pointing instrument is the desired configuration.**

2.4 Expected Performance from a 10 µE Instrument Including Orbit and Attitude Error

To maintain the high-fidelity performance in recovering TVG, the instrument flight implementation requires post-processed precision orbit determination (positioning), and precise pointing (attitude) determination of the interferometer laser orientation within the inertial reference frame and the Earth Fixed Frame. The orbit error is modeled as 1 cm white noise in the radial, cross-track, and along-track directions. The pointing (attitude) error is modeled based on the post-calibration results from ICESat-2 employing high precision star trackers and gyro, as well as a laser reference system: noise = 0.14 arcseconds, bias = 0.3 arcseconds, 0.2 arcsecond 1 cycle per revolution amplitude slow dynamic. These errors are applied to the orthogonal roll and pitch interferometer beam axes. For the flight implementation of the AIGG a laser reference system is recommended to achieve the high interferometer beam pointing accuracies needed for the best performance. The IDL AIGG Study discussed the use of a similar laser reference system.

Figure 9 presents the performance when considering orbit and attitude errors. Orbit and attitude errors do increase the recovered TVG errors, but AIGG's resultant performance advantage is still quite significant,

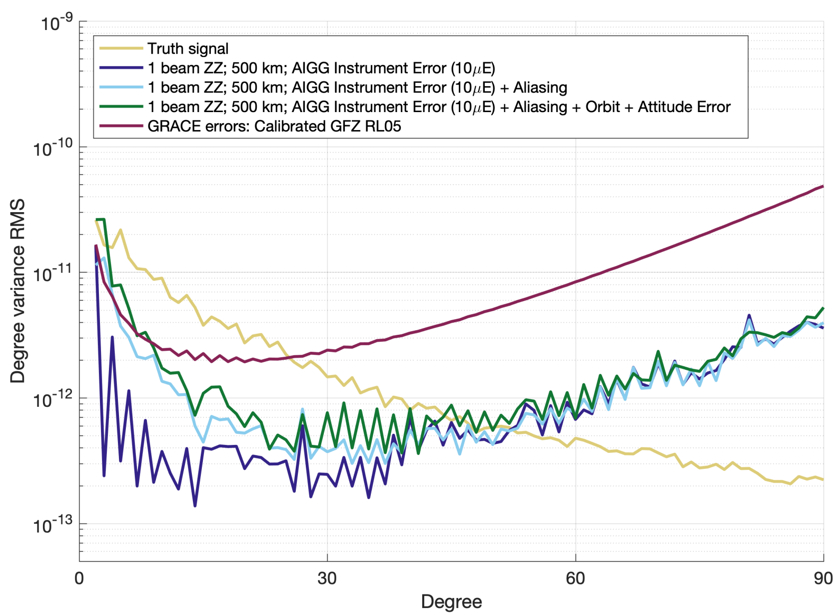


Figure 9. Degree variance of monthly gravity field error spectrums from a 1 beam, radial ZZ, 10 µE sensitive AIGG instrument in a 500 km altitude polar orbit; compared with the degree variance of the truth signal (hydrology, cryosphere, tides, non-tidal atmosphere and ocean) and calibrated GRACE monthly gravity fields. The AIGG error spectrums include: instrument error only; instrument and atmosphere and ocean aliasing; and instrument, aliasing, orbit, and attitude error. The AIGG instrument including all error sources represents a factor of 7 improvement over GRACE for degrees 4–90 (factor of 3 improvement for degrees 4–30, and factor of 8 improvement for degrees 31–90). *The higher the gravity field degree the smaller the spatial resolution of the gravity signal (e.g., degree 30 = 646 km; degree 60 = 329 km, degree 90 = 220 km).*

with a factor of 7 improvement over GRACE. Considering instrument, orbit, attitude, and aliasing errors, a single beam radial pointed AIGG in a 500 km polar orbit with 10 μE sensitivity represents a significant advancement in the performance of TVG observations. This instrument will require a L = 2 m baseline and T = 15 s interrogation time.

2.5 Expected Performance from a Technology Demonstration Mission with Reduced Sensitivity

While launching a full sensitivity 10 μE instrument is the long-term goal to achieve an order of magnitude improvement over GRACE and GRACE-FO from a single satellite, a more near-term technology demonstration mission is highly desired and likely necessary. The technology demonstration mission is necessary to demonstrate the instrument operation and ultimate sensitivity which can only be accomplished in the micro-gravity an orbiting instrument provides. Reducing the size of the instrument from ~3.4 m to ~2.0 m would be achieved by reducing the baseline from L = 2 m to L = 0.5 m. This would represent a degradation in instrument sensitivity from 10 μE to 40 μE/shot. Another approach to reduce size and complexity could be achieved by reducing the interrogation time from T = 15 s to T = 10 s as well as reducing the baseline to L = 0.66 m. This configuration would result in an instrument length of ~2.0 m with sensitivity of 75 μE. Section 3.3 provides a summary of a NASA GSFC Mission Design Laboratory (MDL) study of a 75 μE sensitive instrument technology demonstration mission in a single satellite capable of performance congruent with GRACE and GRACE-FO.

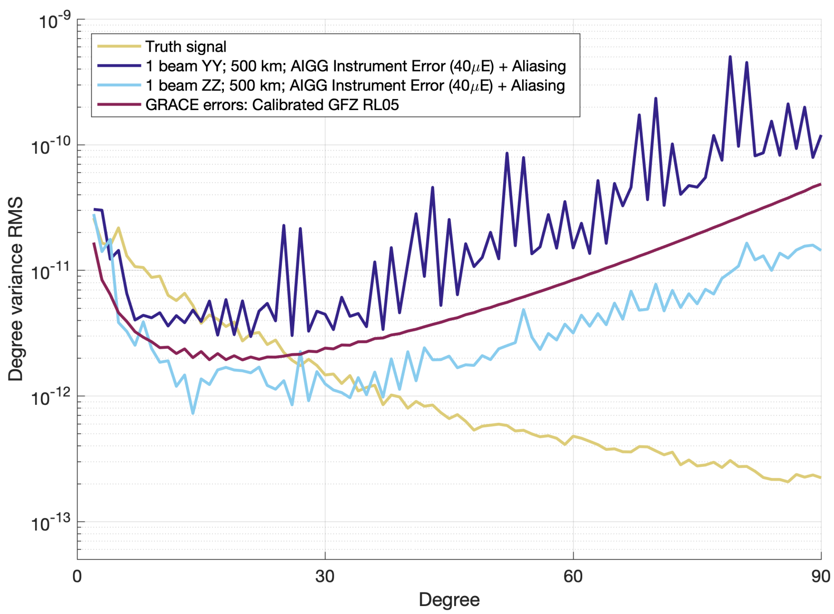


Figure 10. Degree variance of monthly gravity field error spectrums from a 1 beam, 40 μE sensitive AIGG instrument in a 500 km altitude polar orbit; compared with the degree variance of the truth signal (hydrology, cryosphere, tides, non-tidal atmosphere and ocean) and calibrated GRACE monthly gravity fields. The AIGG error spectrums include instrument and atmosphere and ocean aliasing error. The AIGG YY (cross-track) implementation represents a factor of 2.5 degradation in performance over GRACE for degrees 4–90 (factor of 2 degradation for degrees 4–30, and factor of 2.5 degradation for degrees 31–90). The AIGG ZZ (radial) implementation represents a factor of 2.2 improvement in performance over GRACE for degrees 4–90 (factor of 1.5 improvement for degrees 4–30, and factor of 2.5 improvement for degrees 31–90). *The higher the gravity field degree the smaller the spatial resolution of the gravity signal (e.g. degree 30 = 646 km; degree 60 = 329 km, degree 90 = 220 km)*

Figure 10 shows the implementation of a 40 µE sensitive instrument including aliasing error. The YY (cross-track) implementation is a factor of 2.5 degradation in performance from GRACE (degrees 4–90). The ZZ (radial) implementation represents a factor of 2.2 improvement over GRACE (degrees 4–90). As noted above, the degree 2 and 3 zonal terms are not well recovered from GRACE-FO with SLR data used in the estimation of the monthly degree 2 and 3 zonals. Again, given that the beam steering mechanisms are necessary to address post-launch and long-term thermomechanical alignment shifts, the ZZ configuration is the desired implementation.

A 75 µE sensitive instrument represents a logical compromise for a technology demonstration flight instrument and mission. Current engineering analysis and design shows this instrument would have a size of 2.05 m (see MDL study summary in section 3.3) but further engineering could reduce this maximum length. With a ZZ (radial) implementation the instrument would represent a factor of 1.2 improvement over GRACE (degrees 4–90) after considering all error sources including instrument, atmosphere and ocean aliasing, orbit, and attitude errors as shown in Figure 11. While this technology demonstration mission implementation would have reduced size, complexity, and sensitivity, the instrument would still provide significant science contribution. Figure 11 shows the performance of the technology demonstration mission 75 µE instrument relative to a 40 µE, and 10 µE full sensitivity instrument including all error sources. The 75 µE technology demonstration mission, while significantly reducing size and mass, would perform as well as GRACE for degrees 4–90, with SLR data used to recover the very low degree part of the monthly gravity field.

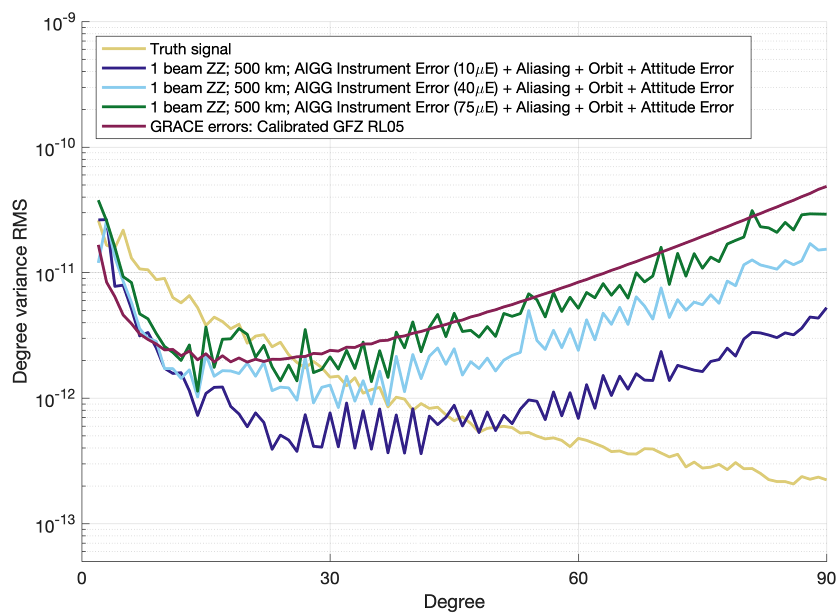


Figure 11. Degree variance of monthly gravity field error spectrums from a 1 beam, ZZ (radial), AIGG instrument in a 500 km altitude polar orbit for instrument sensitivities of 10 µE, 40 µE, and 75 µE compared with the degree variance of the truth signal (hydrology, cryosphere, tides, non-tidal atmosphere and ocean) and calibrated GRACE monthly gravity fields. The AIGG error spectrums include: instrument, aliasing, orbit, and attitude error The 75 µE AIGG ZZ (radial) implementation would require an instrument with length dimension of 2.05 m, and represents a factor of 1.2 improvement in performance over GRACE for degrees 4 -90 (factor of 1.1 degradation for degrees 4-30, and factor of 1.4 improvement for degrees 31-90).*The higher the gravity field degree the smaller the spatial resolution of the gravity signal (e.g., degree 30 = 646 km; degree 60 = 329 km, degree 90 = 220 km).*

3. Technology Readiness, Challenges, and the Path Forward

3.1 Laboratory Prototype Instrument TRL

The AIGG laboratory demonstrator instrument is operating at AOSense, Inc. in Sunnyvale, California. The details of this instrument and demonstration of its current operational status are summarized in section 1.3. The laboratory instrument includes all components necessary to measure the gravity gradient, but those components are not necessarily designed for space flight. Given this configuration, when the instrument is fully optimized and gravity gradient measurements are achieved in the Fall of 2021, the AOSense AIGG will be at Technology Readiness Level (TRL) 4, per definition in Appendix E of NPR 7123.1.

3.2 Space Flight Instrument Design Lab (IDL) Study - 10 μE full sensitivity single beam instrument

The Goddard IDL AIGG Study team developed a conceptual design for the AIGG spaceflight instrument based on the laboratory instrument during a June 2020 IDL study. The purpose of the IDL study was to obtain a first iteration design of a 10 μE full sensitivity single beam space flight instrument with baseline L = 2 m and interrogation time of T = 15 s capable of a factor of 7 improvement in TVG recovery over GRACE when considering all error sources. The study also identified the technological and engineering challenges in developing the space flight instrument.

The IDL started with the current AIGG laboratory instrument design and created a conceptual flight instrument with the primary objectives of identifying:

- Components of lab design that are not space qualified
  - Suggest, where possible, flight qualified replacements
  - Identify components without flight qualified replacements
- Components/subsystems needed for ground testing but not for flight
- Components needed for flight but not in lab design (i.e., compensation for higher rotational rate of spacecraft compared to ground based lab instrument)
- Engineering design work necessary to fly the instrument (data system, structural design, thermal, etc.)
- Accommodation requirements for a supporting spacecraft

The IDL design parameters and assumptions include:

- Measure gravitational gradient to improve time variable gravity models by an order of magnitude
- Launch date: late 2020s
- Mission duration: 3 years plus 2-month commissioning; 5-yr goal
- Orbit
  - Low Altitude: 350-500 km
  - Inclination: 90 degrees
- Instrument reliability: Class C
- Target launch vehicle: Falcon 9 class: 4.6 m (dynamic volume) fairing
- Dedicated mission: no other primary instruments; supporting instruments include magnetometer, accelerometer, star trackers, gyro, GNSS receiver
- In flight instrument pointing orientation: ZZ radial (nadir) pointing

The IDL study products and findings are supporting further design optimization, cost and schedule estimates, and technical readiness and challenges. The flight configuration is shown in Figure 12. It should be noted that further engineering optimization has identified the possibility of reducing the length of the instrument to 3.4 m with theoretical smallest packaging of 2.2m.

The requirements for this full 10 μE sensitivity instrument include:

- Mass: 947 kg
- Power: 1049 W (@28V)
  - RF redesign expected to reduce power by 150+ W
- Data Volume: ~84.6 Gbit/day
- ACS and GNSS
  - Knowledge accuracy of the beam orientation to < 1 arc sec; static and slow dynamic changes calibrated to sub arc sec.
  - Constant Angular Rotation Rate
  - Rate and acceleration information to instrument @10 Hz for rotation and translation compensation
  - GNSS 1PPS signal for OCXO timing reference
- Volume:
  - Hexagonal configuration
  - 1.15 m Height x 4.3m Width

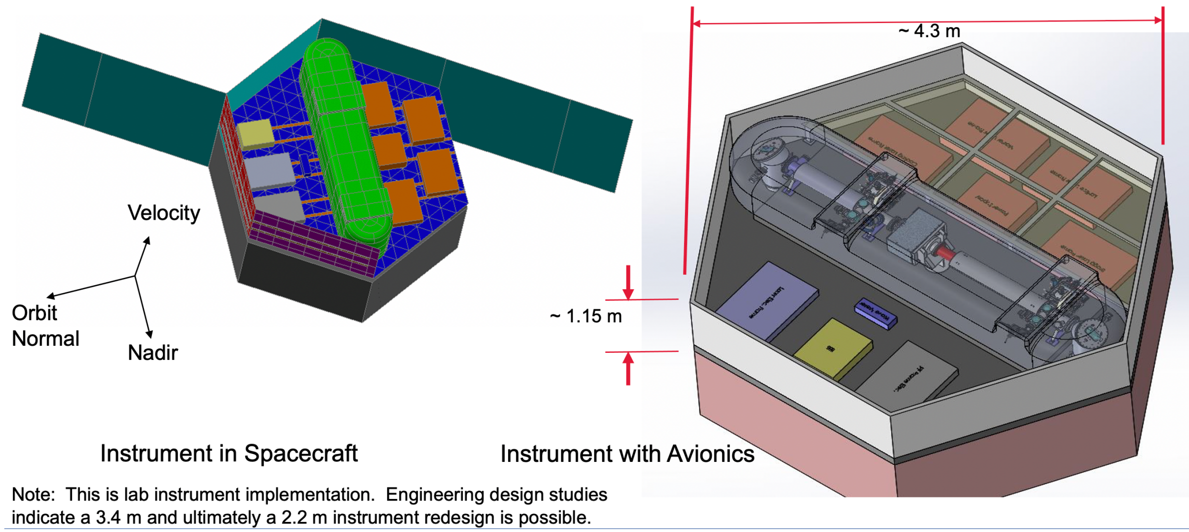
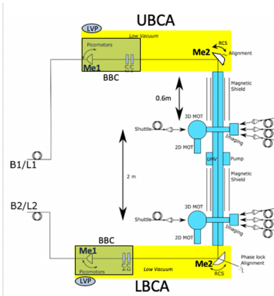


Figure 12. AIGG IDL design configuration for a full sensitivity 10 μE instrument. Engineering design studies indicate a 3.4 m instrument repackaging is possible. This instrument represents a factor of 7 improvement over GRACE from a single satellite that is on the same order in size, mass and power as the two GRACE satellites combined.

When considering the large mass and size of the instrument it is important to understand that this fully capable 10 μE AIGG instrument mass, power, and volume are on the same order as the two GRACE satellites combined. However, the AIGG instrument represents a factor of 7 improvement over GRACE from a single satellite (including all error sources: instrument, atmosphere and ocean aliasing, orbit, and attitude errors).

The IDL Study team identified several subsystems where additional design work was needed on the conceptual design, specifically the laser, RF, and mechanism subsystems. A Goddard Engineering Team is currently working to address those subsystems designs. No major engineering challenges have yet to be identified. The structure and thermal design requires standard engineering practice for spaceflight. The visual readout and data generation of the instrument are easily achievable using standard technology. The mechanisms needed to achieve the rotation compensation are within the state of the practice but are not trivial (Figure 13). Much of the instrument complexity resides within the laser and RF subsystems. It is expected that these subsystems can be achieved with existing components, but the requirements definition and conceptual design are still in work for these (as mentioned above). The TRL of the RF and laser subsystems will be defined after the conceptual design is complete, but TRL-5 is expected (previously achieved performance of a similar device in a relevant environment). The rotation and translation - compensation mechanisms are TRL-5 with similar control achieved for other space-flight missions in different configurations. The rest of the instrument subsystems are relatively low risk and can be considered TRL-6 or standard engineering work.



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Me#	Acronym	Name	Function	Peak Power Input	Duty Cycle	Total Avg power	Axes qty	Total Avg Power
Me1	BBC	Bragg Beam Collimator Or: "Collimating Lens"	Rotate the Bragg laser beam around 2 orthogonal axes	DITs: 2 axes x 1.35W each VCAs: 2 axes x 5W each 232W(*) @20lbf	100%	(2.7+10=) 12.7W	2	25.4
Me2	RCS	Rotation Compensation System (RCS)	Rotate the Bragg laser beam around 2 orthogonal axes	DITs: 2 axes x 1.35W each VCAs: 2 axes x 5W each 232W(*) @20lbf	100%	(2.7+10=) 12.7W	2	25.4
				(*See slide 27)			TOTAL:	51W

Consideration	Incoming Requirement or Assumption	Study Outcome
In-space rotation requirement of BBC	Stationary/low duty cycle	Requires to continuously move at the same time as the RCS mechanism. This necessitated a redesign to proposed VCA/DIT type mechanism
Mechanism launch load survival	None.	BBC picomotors will not survive – redesign required to VCA-type mechanism. RCS actuators will not survive launch, replaced with VCAs
RCS mirror range of travel	Notional estimation	+/-3 deg. on the mirror

Figure 13. AIGG alignment, rotational and translational compensation mechanisms. This engineering solution enables the AIGG to compensate for post-launch alignment changes, slow dynamic thermal-mechanical alignment variation, and rotational and translational motion of the laser beam with respect to the atom cloud over the measurement interval. The solution enables the AIGG to measure the gradient in the ZZ radial direction to maximize signal to noise.

3.3 Tech Demonstration Mission Design Lab (MDL) Study - 75 µE sensitive single beam instrument

An AIGG MDL Study was conducted at NASA GSFC from March 1 – 8, 2021**.** The purpose of the study was to design a technology demonstration AIGG mission that will achieve similar performance as GRACE using an AIGG design with less capability, but with less complexity and smaller size and mass than the IDL instrument. The technology demonstration mission will serve to fully test and verify the on-orbit performance of the AIGG instrument with TVG recovery performance near GRACE performance (Figure 11). While this mission's main purpose is an in-flight technology demonstration, the mission could also serve as a gap filler mission between GRACE-FO and the MCDO mission if required. The AIGG technology demonstration mission will have 75 µE sensitivity from an instrument with overall maximum length of 2.05 m. All key technologies in the instrument, including rotation and translation compensation, will be demonstrated. This AIGG technology demonstration mission will reduce the risk associated with development of an operational AIGG (10 µE sensitivity) which will greatly exceed the GRACE and GRACE-FO capability from a single satellite. A pre-Phase A study award could continue work toward preliminary design of a flight-demonstration AIGG, with a focus on advancing the laser, RF, and mechanism subsystems. A Phase A study award would also establish a cost estimate for the instrument and the overall mission, with a potential target launch in the later part of the decade and as early as 2026.

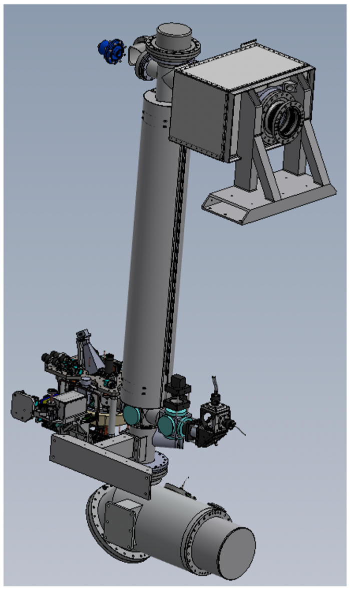

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Figure 14. Technology demonstration instrument overview.

The AIGG technology demonstration MDL study created a conceptual mission point design (Proof of Feasibility) with key system parameters that are consistently represented in all engineering subsystems.

The mission programmatic parameters are the following:

- Mission Class: D
- Mission Life: 13 months
- Launch Vehicle Candidates:
    - Venture Class - Firefly Beta
    - Falcon 9 rideshare via ESPA Grande
- Mission Schedule:
    - LRD: Second half of 2020 decade
- Orbit:
    - Sun-synch 500 km altitude
    - 0600 LTAN

The technology demonstration AIGG instrument is a redesign of the full sensitivity laboratory instrument with significantly smaller size. The mechanical layout of the instrument is provided in Figure 14, and the instrument parameters are summarized below. The instrument Current Best Estimates (CBE) of mass and power are given in Table 1.

Technology demonstration AIGG instrument parameters:

- Total length, 2.05 m
- Gradient baseline, L = 0.66 m
- Interrogation time, T = 10 s
- Large Momentum Transfer, LMT = 6 ħk

Table 1. AIGG technology demonstration instrument mass, power, and data rate current best estimate.

Component	**Total Mass [CBE] (Kg)**	**Avg Power [CBE] (W)**	**Data Rate [CBE] Mbps**
AIGG Sensor Head	270.1	-	-
Laser Frame Assembly	74.7	237.7	-
RF Frame Assembly	43.6	162.0	-
IEB	9.2	155.2	1.4
Misc Instrument Electronics	25.3	143.5	-
Instrument Thermal Control System	111.9	142.8	-
TOTAL	**534.8 Kg**	**841.2 W**	**1.4 Mbps**

The MDL study developed a fully capable spacecraft and instrument integrated observatory to meet the measurement and performance requirements of the science mission. The spacecraft and instrument observatory dimensions are provided in Figure 15, while the observatory coordinate system flight orientation is shown in Figure 16. The observatory stowed dimensions within a Firefly Beta fairing is shown in Figure 17. The maiden flight of the Firefly Beta is scheduled for late 2023. Figure 17 (right) shows the stowed observatory within the fairing with an ESPA Grande ring to facilitate the opportunity for ride sharing.

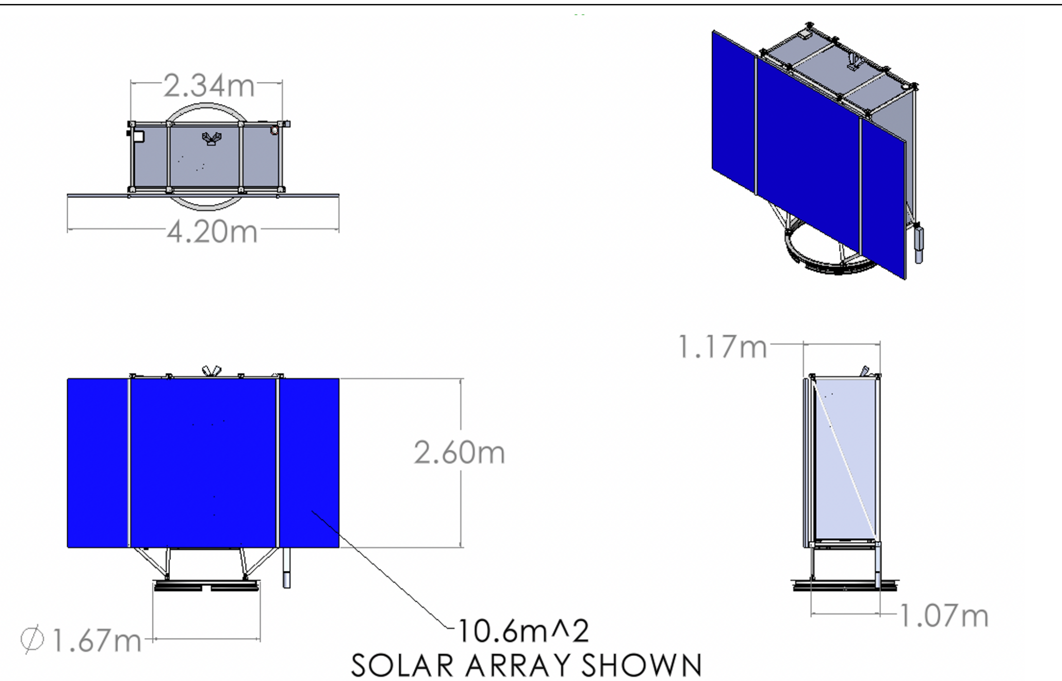

Figure 15. AIGG technology demonstration mission observatory deployed dimensions.

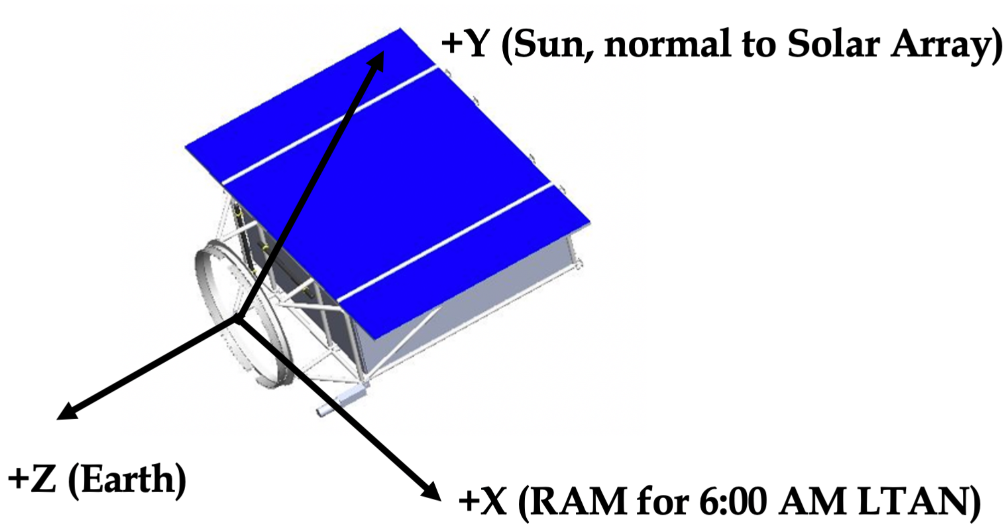

Figure 16. AIGG technology demonstration mission observatory coordinate system flight orientation.

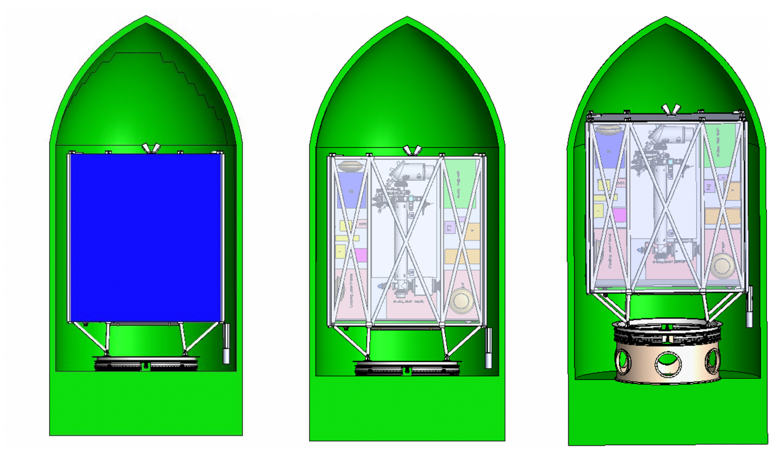

Figure 17. AIGG technology demonstration mission observatory stowed configuration within Firefly Beta fairing (left and middle). The right figure shows the observatory stowed within the fairing with an ESPA Grande ring to facilitate the opportunity for ride sharing.

Figures 18 and 19 illustrate the observatory component and instrument layout.

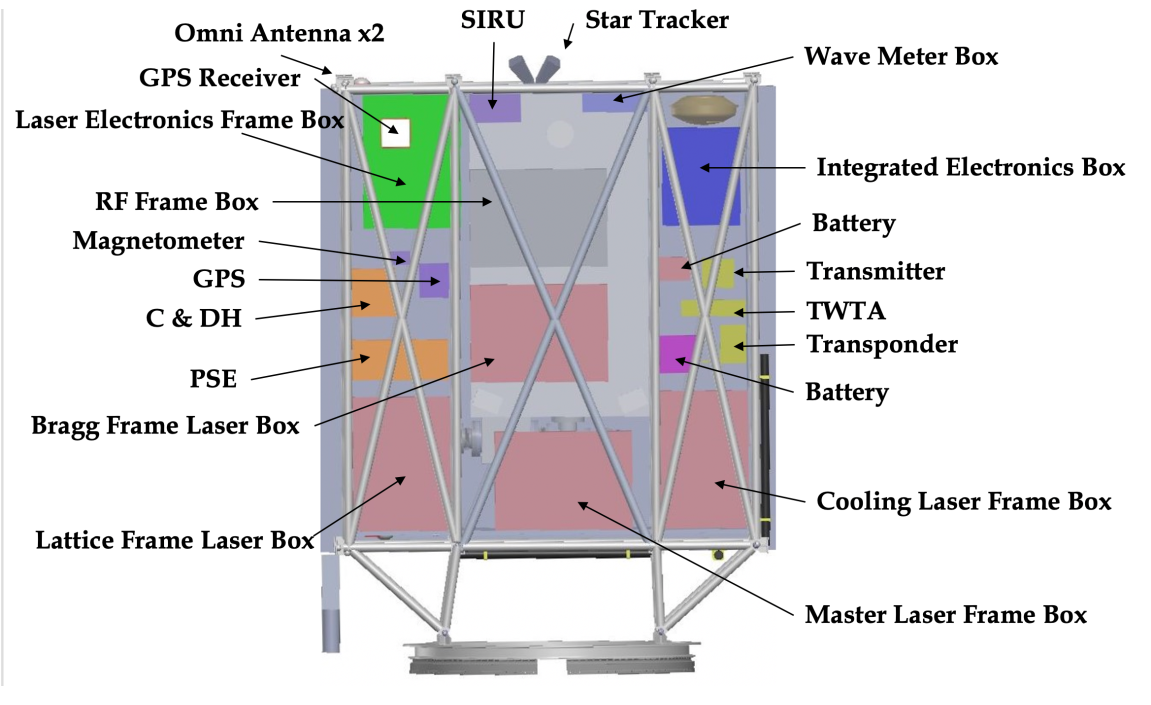

Figure 18. AIGG technology demonstration mission observatory component layout.

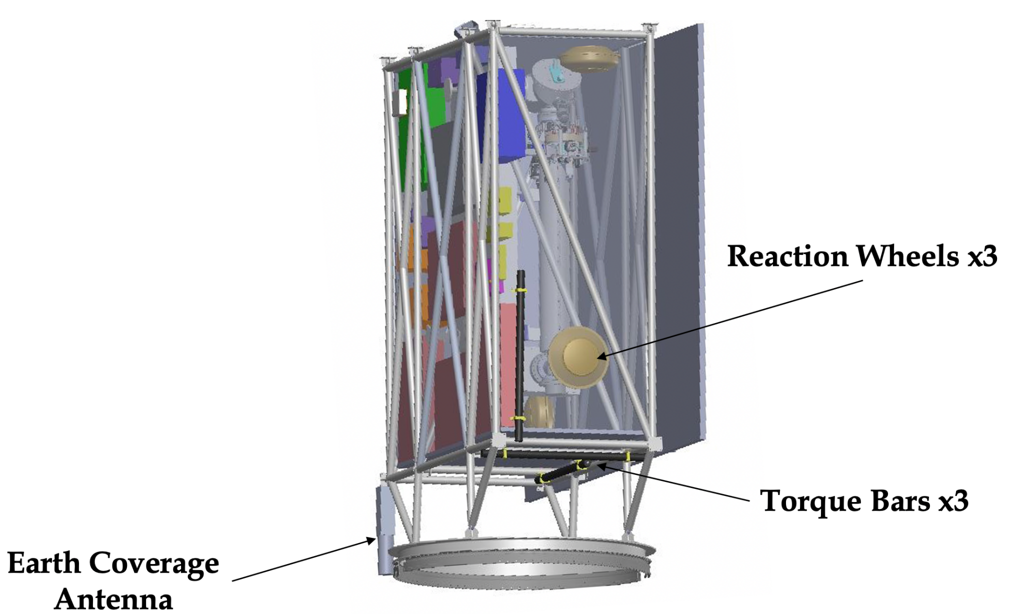

Figure 19. AIGG technology demonstration mission observatory component and instrument layout.

The observatory mass properties summary is provided in Table 2.

Table 2. AIGG technology demonstration observatory mass properties.

Config.	**Mass**	**Xcg**	**Ycg**	**Zcg**	**MOI about SC cg (kg-m2)**		
	Kg (lbs)	cm (in)	cm (in)	cm (in)	Ixx	Iyy	Izz
Launch	1,162 (2,566)	-4 (-1.6)	4 (1.6)	-209 (-82.3)	970	1,260	560
Deployed	1,168 (2,570)	-3 (-1.2)	4 (1.6)	-207 (-81.5)	1,010	1,210	480

The observatory has three main science operating modes to facilitate calibration of the instrument, and to characterize the performance relative to rotation and ACS modes, as well as redundancy in the event of an issue with the rotational compensation mechanisms. These main operating modes include: (1) Inertial pointing where there is minimal inertial rotation. (2) Pseudo inertial where the instrument is pointed along the Earth nadir and then held inertial for several minutes of data acquisition before re-clocking to nadir pointing and holding inertial again. This mode facilitates gradient observation in ZZ, but minimizes inertial rotation during data acquisition. (3) Geocentric where the observatory is continuously rotated at a constant rate to orient the instrument near nadir. This mode requires the use of the rotational compensation mechanisms. Both inertial and geocentric modes have quiet ACS modes where the

Table 3. AIGG technology development mission operating modes.

Mode	Pointing	ACS State	Comm State	Instrument State
Safe Hold	1 RPO	ACS Safe	XMTR Off	Off/Survival
		ACS Safe	XMTR On	Off/Survival
	Inertial	ACS Safe	XMTR Off	Off/Survival
		ACS Safe	XMTR On	Off/Survival
Science Mode	Inertial	ACS Quiet	XMTR Off	On
		ACS Quiet	XMTR On	On
		ACS Wheel	XMTR Off	On
		ACS Wheel	XMTR On	On
	Pseudo Inertial	ACS Wheel	XMTR Off	On
		ACS Wheel	XMTR On	On
	GeoCentric	ACS Quiet	XMTR Off	On
		ACS Quiet	XMTR On	On
		ACS Wheel	XMTR Off	On
		ACS Wheel	XMTR On	On
Launch/Early Ops	Inertial	ACS Wheel	XMTR Off	Off
		ACS Wheel	XMTR On	Off

attitude control is performed without wheels. Table 3 summarizes the operating modes, and Table 4

Table 4. AIGG technology development mission power summary.

Mode	Safe		Science		Science		Science		Science	
	ACS Safe		ACS Wheel		ACS Wheel		ACS MTB		ACS MTB	
	XMTR 30% Duty Cycle		XMTR Off		XMTR On		XMTR Off		XMTR On	
			88 min/orbit		7 min/orbit		88 min/orbit		7 min/orbit	
	CBE	MEV	CBE	MEV	CBE	MEV	CBE	MEV	CBE	MEV
Instrument	100.00 W	130.00 W	841.20 W	1094.00 W	841.20 W	1094.00 W	841.20 W	1094.00 W	841.20 W	1094.00 W
ACS	152.40 W	172.70 W	152.40 W	172.70 W	152.40 W	172.70 W	86.40 W	100.10 W	86.40 W	100.10 W
Avionics	58.30 W	75.80 W	58.30 W	75.80 W	58.30 W	75.80 W	58.30 W	75.80 W	58.30 W	75.80 W
Comm	50.00 W	65.00 W	10.25 W	10.80 W	150.80 W	157.80 W	10.25 W	10.80 W	150.80 W	157.80 W
EPS	8.80 W	11.40 W	8.80 W	11.40 W	8.80 W	11.40 W	8.80 W	11.40 W	8.80 W	11.40 W
Thermal	50.00 W	65.00 W	50.00 W	65.00 W	50.00 W	65.00 W	50.00 W	65.00 W	50.00 W	65.00 W
TOTAL	**419.50 W**	**519.90 W**	**1120.95 W**	**1429.70 W**	**1261.50 W**	**1576.70 W**	**1054.95 W**	**1357.10 W**	**1195.50 W**	**1504.10 W**

provides the details of the observatory power CBE and Maximum Expected Value (MEV).

3.4 Future Development

The AIGG laboratory instrument is scheduled to complete optimization and achieve TRL-4 in Fall of 2021. An MDL Study for a technology demonstration mission was conducted in March of 2021. While the MDL has provided the foundation for a feasible and highly capable technology demonstration mission there are still several items of work while challenges remain. As noted previously, the IDL Study team identified several subsystems where additional design work was needed on the conceptual design, specifically the

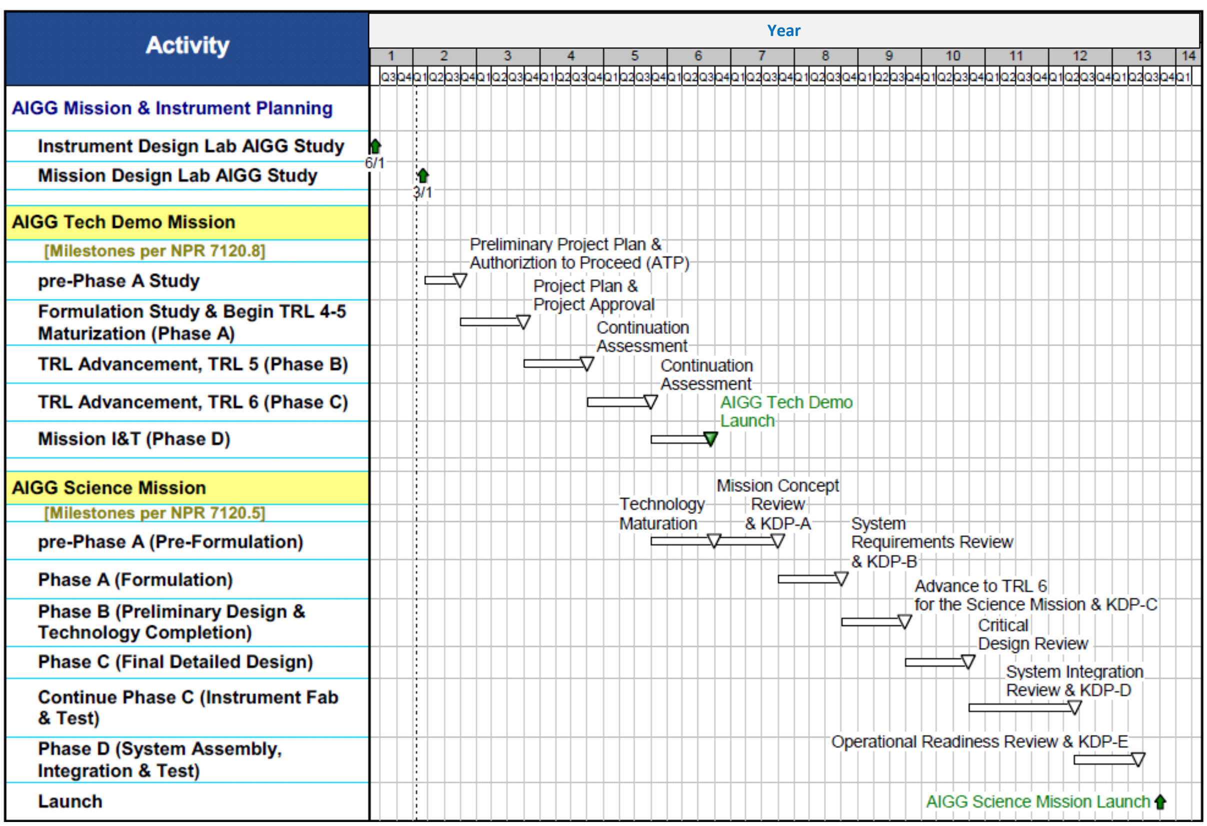

Figure 20. AIGG Notional Roadmap

laser, RF, and mechanism subsystems. Additional detailed design and performance characterization of the technology demonstration flight instrument is needed to finalize the mission and observatory requirements. Further work in observatory disposal and reliability need to be completed, as well as instrument costing. Of high priority is the further design analysis of the instrument to finalize jitter and stability requirements and the performance analysis of the observatory to meet these stringent requirements, which are on the order of less than 1 microrad/sec.

A notional schedule to achieve a technology demonstration mission and follow-on science mission is shown in Figure 20. However, currently there are no funding mechanisms to advance the technology beyond the laboratory instrument TRL-4, nor to take advantage of the information produced by the IDL and MDL AIGG studies. To continue the development toward space flight a pre-Phase A study is the next step and would need to be awarded.

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