The Atmospheric Neutral Density Experiment (ANDE) And Modulating Retroreflector In Space (MODRAS): Combined Flight Experiments For The Space Test Program

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ABSTRACT

The Atmospheric Neutral Density Experiment (ANDE) is a low cost mission proposed by the Naval Research Laboratory to demonstrate a method to monitor the thermospheric neutral density at an altitude of 400 km. The primary mission objective is to provide total neutral density along the orbit for improved orbit determination of resident space objects. The ANDE mission also serves as a test platform for a new space-to-ground optical communications technique, the Modulating Retro-reflector Array in Space (MODRAS) experiment. Both are sponsored in part by the Department of Defense Space Test Program.

The mission consists of two spherical spacecraft fitted with retro-reflectors for satellite laser ranging (SLR). One spacecraft is completely passive; the other carries three active instruments; a miniature Wind And Temperature Spectrometer (WATS) to measure atmospheric composition, cross-track winds and neutral temperature; a Global Positioning Sensor (GPS); and a Thermal Monitoring System (TMS) to monitor the temperature of the sphere. A design requirement of the active satellite is to telemeter the data to the ground without external protrusions from the spherical spacecraft (i.e. an antenna). The active satellite will be fitted with the MODRAS system, which is an enabling technology for the ANDE mission. The MODRAS system consists of a set of multiple quantum well (MQW) modulating retro-reflectors coupled with an electronics package, which will telemeter data to the ground by modulating the reflected light from laser interrogation beam.

This paper presents a mission overview and emphasis will be placed on the design, optical layout, performance, ground station, and science capabilities of the combined missions.

Keywords: Satellite laser ranging, optical communications, atmospheric drag.

1. INTRODUCTION

Significant advances in the miniaturization of space technology and cost reduction has supported the proliferation of micro satellites. Where once a single satellite contained a suite of instruments to support several mission objectives, often times not all related, current micro satellites are tailored to accomplish a small set of related objectives. Through the use of micro satellite technology, NRL is building a satellite suite to improve precision orbit determination and prediction of Low Earth Orbit (LEO) by monitoring total atmospheric density at 400 km. The suite consists of two spherical satellites with instrumentation to perform these interrelated mission objectives: first, to provide high quality satellites, with stable and well determined coefficient of drag, for calibrating precision orbit determination models; second, to test retro-modulator-based optical communications as the primary command and telemetry downlink for satellite operations; and finally, provide detailed atmospheric composition for validating new Air Force sensors.

The major source of error in determining the orbit of objects in LEO, altitudes less than 1000 km, is the computation of acceleration due to atmospheric drag. This acceleration is governed by the equation,

$$a = -1/2(C_D A/m)\rho v^2$$

where a is the acceleration, C_D is the coefficient of drag, A is the cross-sectional area perpendicular to the velocity direction, m is the mass of the object, ρ is the atmospheric density and v is the orbital velocity relative to the medium. There are several atmospheric density models routinely used in orbit determination. These include the Jacchia 1970, J70, empirical model derived from satellite observations[1], the Mass Spectrometer Incoherent Scatter Radar Extended, MSISE-90, model[2,3] and the recently revised NRLMSISE-00[4]. The quantity ($C_D A/m$) is commonly referred to as the inverse ballistic coefficient[5], B. The quantity measured with this method is the product of the ballistic coefficient and the density. Hence, to retrieve atmospheric densities from orbital observations one must have adequate knowledge of the ballistic coefficient and the relative velocity with respect to the medium. For example, consider a sphere of known mass in LEO. The cross-sectional area of a sphere is independent of orientation and is therefore constant. Assume the sphere does not have any expendables such as fuel for attitude control thrusters; therefore the sphere's mass is constant. For this example, a high fidelity C_D model can be used to compute the C_D of the sphere for different conditions the sphere will experience in orbit. Inputs to such a model include the properties of the surface material of the sphere, the temperature of the sphere, and the temperature and composition of the atmospheric constituents impinging the surface of the sphere[6]. The velocity of the sphere can be obtained from the orbit determination, while the velocity of the atmosphere can be modeled using an atmospheric wind model such as the Horizontal Wind Model (HWM)[7]. Results from a four-month period monitoring the Mir spacecraft are presented in Figure 1. Note that the altitude of the Mir is decreasing; an orbital maneuver was performed in May to boost the perigee of the spacecraft. Also plotted are the solar F10.7 cm flux, a monitor of solar activity that directly affects the thermosphere, and the daily average A_p index, a monitor of geomagnetic activity. Total atmospheric density for each of the three models discussed above is plotted. Note that the three models track each other for most of the large trends although small deviations are present.

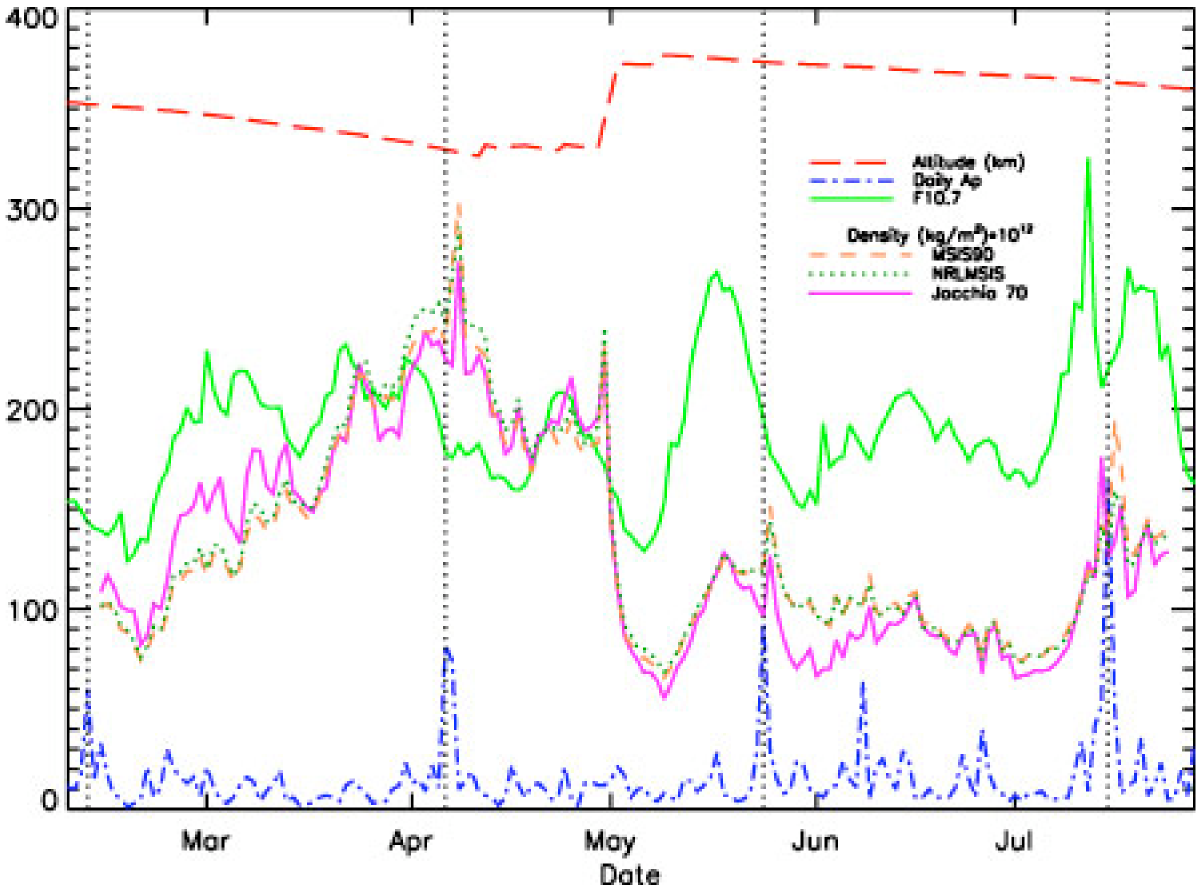


Fig. 1. Solar (F10.7 cm flux) and geomagnetic (daily averaged A_p) indices for Feb.-Aug. of 2000. The altitude of the Mir space station is plotted as well as the atmospheric density derived from observations of the Mir using three atmospheric models (J70, MSISE90, and NRLMSIS00). Four periods of high geomagnetic activity are highlighted with vertical dotted lines. Note that the density derived from the observations increases shortly after the activity. Several Mir thrusting maneuvers are evident in the altitude plot, most notable in the beginning of May.

The concept of the ANDE mission is to build and fly two satellites in a lead-trail 400 km circular orbit as depicted in Figure 2. The US Space Surveillance Network (SSN) as well as domestic and international satellite laser ranging (SLR) sites will make routine observations of the satellites. The satellites will consist of two spheres constructed to the same dimensions but from different surface materials. The satellites will have a known mass ratio (2:1) and a mission lifetime of 1-3 years depending on solar activity. The radar cross section (σ_{rcs}) of each sphere will be determined in the laboratory prior to launch. GFZ-1 drag calculations indicate that the C_D variation around an orbit ranges from 2.06 to 2.11 due to thermal and atmospheric composition effects[6]. Time varying high fidelity C_D modeling shows the potential to improve atmospheric densities derived from satellite observations[6]. Detailed high fidelity C_D modeling of both spheres will be performed prior to launch. This modeling includes surface area effects, normal and tangential momentum accommodation factors (as a function of incident angle and energy), surface composition and roughness, surface temperature. The σ_{rcs} will be measured in the laboratory to provide an accurate value for use in the calibration of the Naval Space Surveillance

System radar fence. Both spheres will be fitted with retro-reflectors (a set of three planar mirrors configured such that photons are reflected back along the angle of incidence) for SLR capabilities. One satellite will be passive and the other fitted with instrumentation and control hardware to receive commands and telemetry data to the ground. The configuration of this mission is designed to address several scientific and operational needs.

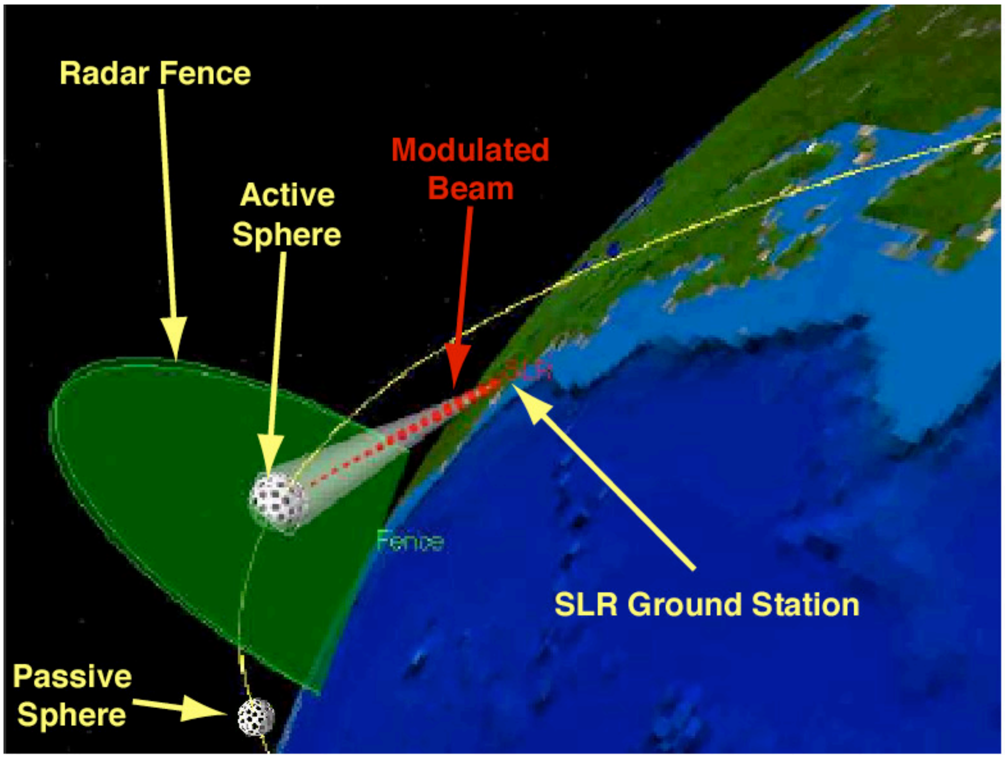


Fig. 2. A visualization of the lead-trail orbit for the ANDE mission. The SSN radar fence and a sphere populated with retromodulators (Active Sphere) with an SLR ground station are highlighted.

Traditionally in orbit determination the position error associated with atmospheric drag is about 15-20%, Marcos et al.[8] have shown that the use of an atmospheric correction parameter derived from the observations of a single calibration object can be applied to other objects in LEO to improve the determination of those object's orbits. The USAF has initiated the High Accuracy Satellite Drag Model (HASDM)[9] to expand on this technique using approximately 60 LEO objects as calibration targets and sophisticated inversion and filtering algorithms. HASDM is designed to specify global total atmospheric density. The accuracy of the density specification will be limited by the number of position observations and the knowledge of the target's ballistic coefficient. Due to the unique attributes of the ANDE mission (constant A, no mass loss, stable radar cross section, well modeled C_D); routine observations of the ANDE spheres would provide exceptional calibration targets for the HASDM program. The purpose of flying two spheres in a lead-trail orbit allows the study of different surface materials, an important validation point for current drag coefficient models.

In orbit, the satellites will slowly separate from each other due to the difference in mass. Precise monitoring of the satellites position with SLR will provide an opportunity to study small scale, spatial and temporal variations in drag associated with geomagnetic activity. The Naval Network and Space Operations Command (NNSOC) is in the process of upgrading the radar fence for the space surveillance network. Additionally, since the two objects have known σ_{rcs} and SLR capabilities, observations of these satellites will provide optimal calibration targets for the radar fence maintained by the NNSOC. Use of SLR for calibration of the Fence has become part of Operations[10].

In the near future (early 2003) the Defense Meteorological Satellite Program (DMSP) will launch the first of five Block 5D3 spacecraft. These satellites have been upgraded with a suite of new near Earth space environment sensors. One such sensor is the Special Sensor Ultraviolet Limb Imager (SSULI), which measures the Earth's naturally occurring ultraviolet emissions. Atmospheric density profiles (75-750km) are derived from these observations every 90 seconds (about 5° in latitude) along the orbit of the DMSP spacecraft. An important aspect of the SSULI Program is the validation of the sensor products. Drag derived densities from the ANDE mission will provide a validation point for the SSULI derived densities at 400 km.

The active sphere of the ANDE mission will also serve as a proof-of-concept test platform for a space-to-ground optical communications system. The experiment makes use of multiple quantum well (MQW) retromodulators distributed in such a ways as to provide insight into scintillation effects and partial coherence on transmission of data streams through the atmosphere (http://mrr.nrl.navy.mil).

2. ORBIT INSERTION

To meet collision avoidance forecast requirements at space shuttle and ISS altitudes, an improved atmospheric specification is needed. The ideal orbital parameters to support the atmospheric specification derived from the collision avoidance requirement are a circular orbit between 400-450 km altitude with an inclination of 51.6°. The Air Force Space Test Program (STP) is providing launch and deployment services for the mission. The Space Shuttle will serve as the launch vehicle. To assure spherical symmetry of the spacecraft a design requirement was levied on the mission to insert the spacecraft into orbit without the use of a permanent mechanical interface on the spacecraft. The Space Test Program has designed a unique payload ejection system for this mission as well as other future Department of Defense missions. This system will insert both spheres into orbit simultaneously. A risk reduction flight is scheduled for late 2003 (see section 7).

3. PASSIVE SATELLITE

The passive sphere design is currently under final review. The sphere is 0.4826 m (19.0 in) in diameter, which dictates a cross-section area of 0.1829 m^2, and constructed of two spun metal aluminum 6061-T6 hemispheres with a wall thickness of 1.27 cm (0.5 in) and a total mass of 25.0 kg. The two hemispheres are joined through a 2.54 cm (1.0 in.) thick Teflon disk, with alignment of the hemispheres maintained through two internal aluminum plates, one on either side of the Teflon disk. Thirty 1-cm retro-reflectors are distributed on the sphere in latitudinal bands. There are three bands per hemisphere: one retro at ±90º, six retros at ±52.5º, and eight retros at ±15º. A mechanical drawing is provided in Figure 3 for reference. This provides a laser ranging cross-section, σ_{LCRS}, of greater than 10^4 m^2 for all passes with elevation angles above 20° as detailed in Figure 4. To provide a distinct C_D from the other sphere, the outer surface of the sphere will be covered with Kapton, a material commonly used in spacecraft thermal blanket construction.

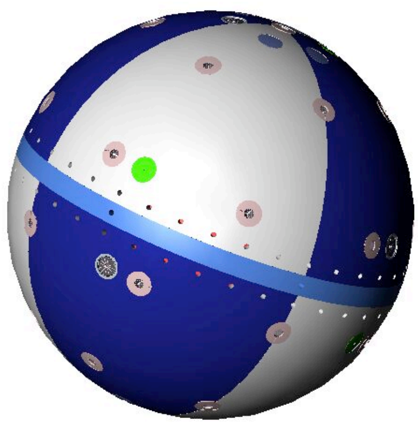


Fig. 3. A Drawing of the passive ANDE sphere. The diameter is 0.4826 m with a thickness of 1.32 cm. Locations of the retroreflectors are shown along with the mating junction for the two hemispheres

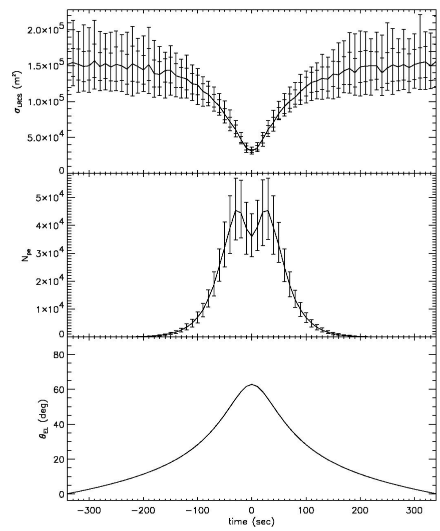


Fig 4. A SLR radar cross-section (top), returned photo electrons (middle), and elevation angle with respect to observing station (bottom) of the ANDE passive sphere as a function of time for one pass.

4. ACTIVE SATELLITE

The active sphere is currently in the preliminary design phase. This satellite is both a density validation experiment as well as a new technology communications demonstration. The active sphere will have the same outer dimensions as the passive sphere (and therefore the same cross-sectional area) but it will have approximately twice the mass (~50 kg). On this sphere, retromodulators will replace the passive retros and will be distributed non-uniformly. This sphere will also carry active instrumentation to monitor the *in-situ* environment. The data will be down linked via the retromodulators. Table 1 provides a list of the components. Power for the active sphere is supplied by an array of thin film copper indium gallium diselenide (CIGS) photovoltaic arrays developed by ITN Energy Systems and a set of primary and rechargeable batteries. The solar arrays are mounted flush with the surface between the retro reflectors. Total power available to the active sphere is about 10 W. Table 2 provides the mass and power budget for the spacecraft. For C_D considerations, the active sphere will be coated with a layer of SiO_2 similar to the outer layer of photovoltaic construction.

Table 1. Components of the active satellite and their functions.

Component	**Measurable/Function**
CPU/State Machine	Central processing
Photovoltaic Array	Power
Batteries (primary & rechargeable)	Power
Thermal Control System	Active control of spacecraft temperature
Thermal Monitoring System	Surface temperature of the sphere
Mass Spectrometer	Number density of atmospheric constituents from 1-46 amu
GPS Receiver	Position of spacecraft
Modulating Retro-Reflector Array	Telemeter data to ground
Backup Communications System (PCSat)	Heartbeat telemetry

Table 2. Active sphere mass and power budget.

Component	**Mass**	**Power**
Novatel OEM-4 GPS Sensor	3.2 kg	3.2 W
Thermal Monitoring System	2 Kg	1.0 W
Wind And Temperature Spectrometer	300 g	200 mW
Modulating Retro-Reflectors	10 g x 16 = 0.2 kg	130 mW x 16 = 2.1 W
MRR Electronics	TBD	TBD
Photodetectors (# TBD)	10 g each	300 mW each
Backup Communications (145 MHz)	2 kg	500 mW
CPU/State Machine/Data Storage	1 kg	2W
Power Supply (Primary & Secondary Batteries, Photovoltaic Arrays)	TBD	TBD
Structure	50 kg – above	N/A
Total	**50 kg**	**9.3 W**

5. COMMUNICATIONS

The NRL modulated retro-reflector (MRR) system consists of an array of optical retro-reflectors, each coupled with a multiple quantum well (MQW) electro-absorptive shutter[11,12]. The operation overview of this system is presented in Figure 5. An incident laser beam illuminates the device from an interrogation platform. When a low voltage (on the order of 10-18V) is applied to the MQW device, the shutter goes transparent allowing photons from the interrogation beam to enter the system. The photons are then reflected back along the original angle of incidence by the retro-reflector. The modulated retro-reflected return, carrying the data stream, returns the signal to the interrogation platform. This technique provides a compact, low power (150 mW per device), lightweight (less than an ounce per device) two-way optical communication platform. The NRL corner-cube devices can support up to 12 Mbps and has been demonstrated to support real-time video at 30 fps using wavelet compression[13]. The devices can be made to operate with a 10 nm bandwidth at 850 nm, 980nm, 1.06 nm, or 1550 microns. A photo of a 980 nm MQW modulator is shown in Figure 6.

For the MODRAS experiment, the field-of-view (FOV) of the mounted device will be on the of the order of 45 degrees FWHM and the operation wavelength will be 1.05 microns. One hemisphere of the active sphere will be fitted with an array of these devices customized at 1.05 microns. The devices will be situated about the sphere in a cluster at the top and singly at near-cardinal points on the sphere. This non-uniform distribution will enable differentiation of scintillation effects from partial coherence effects on the returned data stream. The system's nominal data transmission rate will be 10 Kbits/second with test modes of up to 1 Mbit/second. Through unique coding of each device, the illuminated modulating retro-reflector in the returned data stream can be identified enabling determination of orientation and other parameters[14]. In MODRAS, the attitude and spin rate of the active sphere will be determined using this discrimination method. The two ground sites intended for use in the MRR communications experiment are the Air Force Maui Optical Station at Haleakala, Maui, and the NRL Midway Research Facility in Quantico, VA.

A backup communications system is being designed to telemeter limited data packets to the ground at amateur radio frequencies (145 MHz). This system, being designed by the United States Naval Academy (USNA), uses the spherical symmetry of the satellite as an antenna. A one inch non-conducting gap is required between the two hemispheres, enabling the spacecraft itself to act as a dipole antenna at 145.825 MHz. This system will activate every two minutes and broadcast a data packet containing temperature information from the spacecraft.

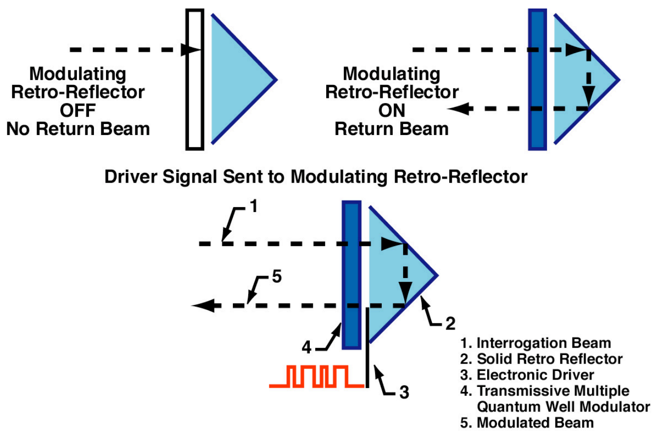


Fig. 5. An operational overview of an MRR.

Fig 6: A photograph of a multiple quantum well modulator.

6. CONCEPT OF OPERATIONS

The concept of operations for the ANDE/MODRAS combined mission is fairly simple. After orbit insertion, the spheres will be tracked by the SSN who will provide accurate orbital state vectors for each sphere. The SLR site can then use these state vectors to acquire the spheres with the laser. A typical SLR site can operate with elevation angle between 20° and 85° and can track objects down to approximately 300 km. An access simulation was performed for spheres at 400 km (beginning of life) and 300 km (near end of SLR tracking limit) for the SLR ground site located at the NRL Midway Research Facility in Quantico, VA and Air Force Maui Optical Station at Haleakala, Maui, (these are the two sites that will be capable of MRR communications). In order to obtain good statistics, a simulation was performed over a one year time span. These results are presented in Figure 7, which consists of a histogram plot of the duration of the access in 10-second bins. Typical access times are on the order of 3 minutes and 2 minutes with initial altitudes of 400 km 300km altitude respectively. The gap between accesses is usually less than one day.

The instruments will be operating continuously, storing data to be transmitted on the next access. Mission lifetime should be about 2-3 years for the active sphere (depending on solar activity and initial orbital altitude) and one year for the passive sphere (due to its smaller mass).

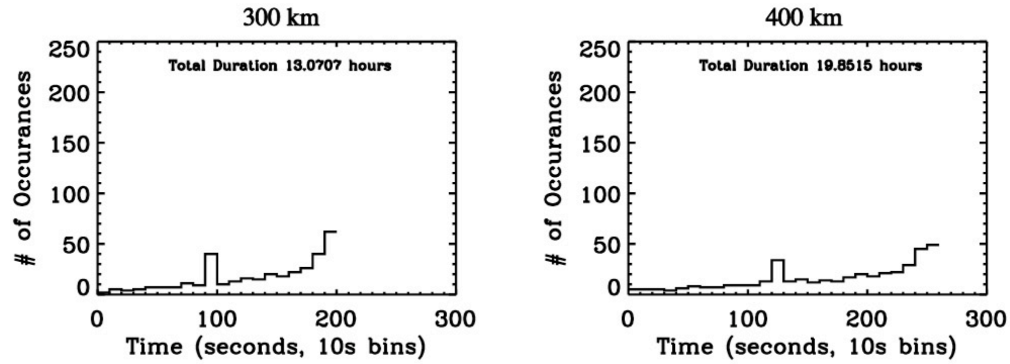
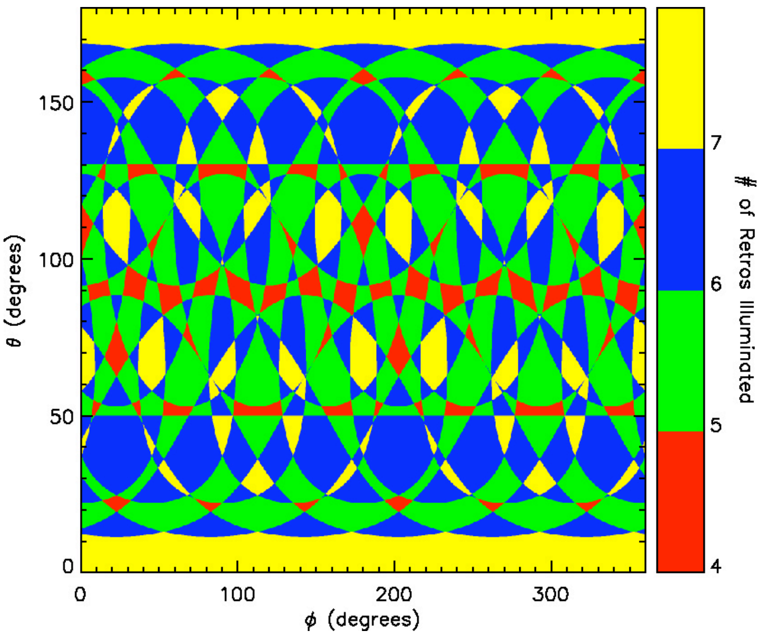


Fig. 7: Histogram plots of the access time for a sphere in a circular, 51.6° inclination orbit at 300 and 400 km altitudes.

7. RISK REDUCTION MISSION

The Space Test Program intends to test the deployment mechanism on a shuttle mission in late 2003. A risk reduction experiment for this mission is currently being constructed at NRL. The primary goal of the mission is to verify the capabilities of the orbit insertion mechanism. Secondary goals for the mission include spin axis and orientation, which are critical for temperature stabilization and link closure for the onboard instruments and retromodulators in the ANDE/MODRAS mission, space qualification of the backup communications system, and space qualification of the CIGS photovoltaic arrays. The primary payload for the risk reduction mission consists of a spherical spacecraft with the same size and mass as the ANDE active spacecraft. The spacecraft will be fitted with 12.7 mm diameter optical retro reflectors using the same layout as the passive ANDE sphere; latitudinal bands at ±90º, ±52.5º and ±15º with one, six and eight retros per band respectively. Figure 8 presents the number of retro reflectors illuminated as a function location on the sphere (in longitude and latitude) to the observer.

Four methods of determining the spacecraft spin rate and/or orientation have been designed. The first method uses data from the sample CIGS photovoltaic arrays, located at the endpoints of three mutually orthogonal axes through the center of the spacecraft. The voltage, current and temperature of these devices will be the transmitted to the ground by the communications system every two minutes. The arrays facing the sun or albedo of the Earth will have a larger current than those facing deep space. These data will be tagged in time and location on the sphere allowing for post-processing on the ground to determine the spin rate and orientation of the sphere. A second method to determine the spin axis/orientation is to observe sunlight glinting off of the front surface of each retro reflector with a ground-based telescope. This provides a purely geometric method of attitude determination. The last two methods involve observations of the



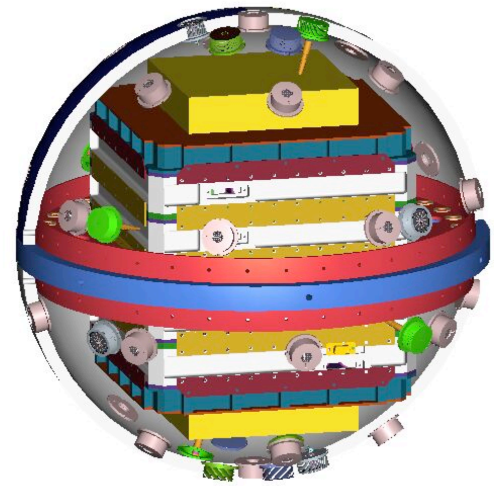


Fig. 8. The number of retros illuminated as a function of longitude and latitude on the sphere.

Fig. 9. Exploded view of spacecraft showing hemispheres (grey), the non-conducting separator (blue), the two payload mounting decks (red), battery and payload area (grey, blue, yellow) and the retro-reflector array (pink)

spacecraft via the AMOS. The outer surface of the sphere is anodized aluminum which randomly polarizes light it reflects. A pattern will be painted on the sphere with Aeroglaze A276 gloss white polyurethane paint. This paint will preserve the polarization of light it reflects. The HI-CLASS laser, which operates at 11.15 mm, will illuminate the sphere with a linearly polarized beam when it passes over the AMOS site. AMOS telescopes are capable of determining the polarization of the light they detect. By observing the change in the polarization of the light returned from the spacecraft as a function of time one can determine the spin rate and possibly the orientation of the sphere. The final method is to fit the spacecraft with six laser diodes, each with a discrete frequency, oriented in a similar fashion to the photovoltaic arrays. These laser diodes will only be activated on passes over the AMOS site. Observations of the sphere will be made as it passes over the site via telescope. The spin rate and orientation can be calculated by determining which laser diode was emitting the observed light as a function of time.

The communications system is designed to operate at 2 W ERP at 145.825 MHz with a 20 MHz bandwidth. The system runs on 9 Volts, supplied by a series of lithium primary batteries. Total capacity of the battery bank will be about 320 AHrs, enough to power the system (which draws 17 mA on a 10% duty cycle) for about two years. An expanded view of the spacecraft is provided in Figure 9 which details the payload sections as well as the non-conductive separator.

8. SUMMARY

The ANDE/MODRAS combined mission is a low cost constellation of micro satellites designed to support improvements in orbit determination and prediction, and to demonstrate re-modulation as a means of low power, compact optical communications from space. The arrangement of two spacecraft in a lead-trail orbit with identical cross-sectional areas provides an exceptional set of targets to study C_D modeling and its effect on satellite drag. The active satellite contains instrumentation to test the feasibility of an optical communications link from space to ground. The data retrieved from the active satellite will be used to validate UV derived densities from the DMSP satellite. Retroreflected modulated data from the MODRAS experiment will provide insight into the challenges of obtaining optimized signal return through a complete atmospheric channel. This mission will demonstrate the effectiveness of flying low cost calibration targets to support Department of Defense and NASA requirements for precision orbit determination and collision avoidance. In addition, data from this mission will be used to improve the scientific understanding of the interaction between a spacecraft and its environment.

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