Principle Investigator Melville Ulmer
Northwestern University
Development of a normal incidence deployable telescope for the EUV
Short title:nOrmal inCidence dEpLOyable Telescope (OCELOT)

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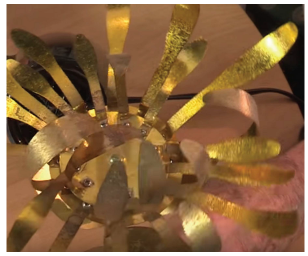


1 Executive Summary

EUV astronomy has languished since the EUVE mission whose scientific justification was to study strong EUV emitters such as white dwarfs. There are at least 2 reasons for the delay of a new EUV (defined here as about 10-90 nm), mission. First, the interstellar medium (ISM) is relatively absorptive at EUV wavelengths e.g., [1]. Therefore at the time of the EUVE launch there were judged to be a relative dearth of high interest objects that could be observed. The advent of the discovery of exoplanets has changed the level of interest in EUV astronomy, however. Now, the EUV environment of exoplanets has taken on great importance in the search for extraterrestrial life. ~~For,~~ the EUV loading via the host star will determine which stars could harbor planets on which life could, and the study of the EUV flux from late-type stars is still in its infancy [2, 1]. As shown in [3], there are almost 500 stellar targets of interest to exoplanet science mission that uses no major technology breakthroughs.To quote from page E-12 Astro 2020, “The host star impacts planetary atmospheric loss, composition, and climate, and the host star’s spectrum (including X-ray/EUV flux), activity, and long-term luminosity evolution are critically important for understanding the dynamic habitability of exoplanets. ~~Exoplanet surveys have shown that terrestrial planets can exist.~~” Further evidence of NASA’s renewed interest in EUV astronomy is the funding of NE~~e~~xtUP study [4].

Second, a paradigm shift in technology is called for to enable, at reduced cost over current capabilities, greatly improved EUV sensitivity. Therefore, the purpose of our *OCELET* project to provide the technology base for a normal incident multi-layer deployable space telescope mirror of about 1 m in diameter that could be flown on a CubeSat or SmallSat.

Our project builds on our own recent work which demonstrates there is a high likelihood of success in a proposed proof of concept. In summary, the major questions we answered are: (1) Prototype test sheets of NiTi (Shape Memory Alloy; SMA here after) can been trained to return to shape to better than 1 μm; (2) These sheets can be plated with high phosphorous content electroless nickel (eNiP hereafter); (3) and eNiP is well known to be able to be polished to the the 0.3 nm level e.g., [5]. For our proposed effort to achieve the short scale-length (high frequency in FFT surface analysis jargon) an additional smoothing step is required. The PI’s group successfully applied the CNx coating developed at Northwestern (NU hereafter) to fabricate working multilayers for grazing incidence electroformed X-ray optics[6]. Thus, the team is well positioned to combine the technologies in hand to make a deployable normal incidence EUV mirror. Thus after a shape setting NiTi sheets flat, we will eNiP plate *including development of a process to minimize the distortion of NiTi due to plating stress*, *super polish*; *overcoat with CNx*, *coat with Mo/Si multilayers such as used by [7]*, *verify ML reflects at EUV normal incidence*, *carry out a pseudo stow and deployment*, *measure EUV normal incidence reflectivity* ~~or~~ the deployed optic.

We plan to demonstrate that the eNi on NiTi can be made smooth enough and that these multilayers remain intact after a stow and deploy step. The NiTi substrate is SMA, which has by design, a special crystalline structure. Thus, until we prove, as we propose to do here, it could be argued that the multilayers deposited on on the CN_x+eNi+NiTi will not retain their functionality. We therefore propose to demonstrate that the process will work. To accomplish our goal achieving ~~TL~~3, we have a team of experts in all phases of the project plus collaborators to guide us on the goals of our technology as applied to EUV astronomy.

2 Introduction

Only in the past few years has it been noted that being in the habitable zone as defined by the bolometric luminosity of the host star is ~~nto enough~~ to prove ~~the zone it habitable. For, the stellar high-energy radiation environment is likely determinant of long-term habitability and the formation of life on exoplanets (Figure 1)~~.

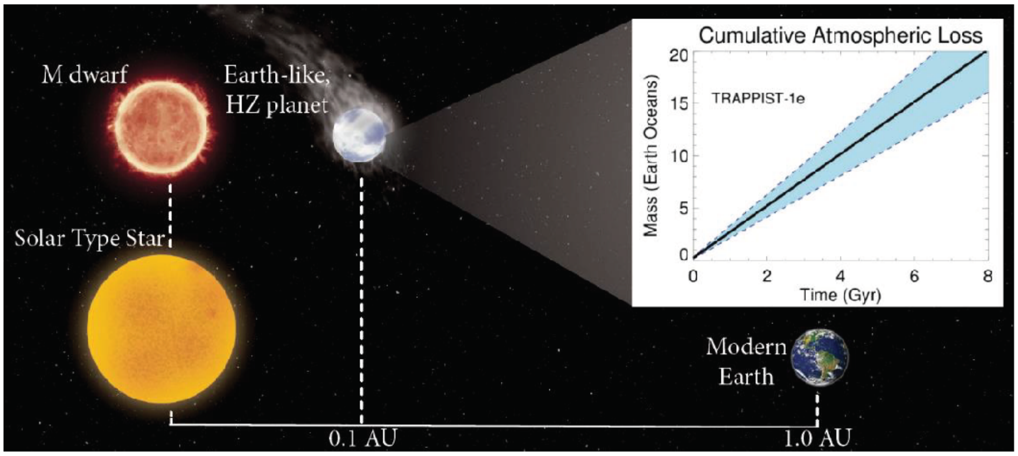


Figure 1: This figure is, with permission, from [3]. Temperate, rocky planets around M dwarfs may rapidly lose 10 – 20 Earth oceans (or 2,500 – 5,000 1 bar atmospheres) over their lifetimes ~~their atmosphere~~ due to high stellar EUV fluxes in the HZ. The inset shows a mass-loss simulation for the most promising HZ planet in the Trappist-1 system (shaded region are uncertainties from FUV observations; [8]) ~~This demonstrates why new higher sensitivity missions of the type the *OCELOT* concept can enable.~~

Thus, as part of the major Astro 2020 Science Theme "Worlds and Suns in Context" (cf. Astro2020-slides.pdf slide 6) scientists will be asking what fraction of temperate, rocky planets around stars of different types are able to retain a habitable atmosphere? However, UVOIR will ~~not~~ be capable of observing a primary driver for atmospheric physics and evolution: the EUV radiation produced by the host stars~~.~~ See [8] and ~~also~~ [9]. *Therefore, technology to enable great advances in EUV astronomy are needed now so that complementary EUV missions can be flown ahead of UVOIR.*

3 Summary of proof of concept plan

The project we propose here a spin-off of funded R&D project to develop proof of concept for a deployable visible-light space mirror. The design combines two advanced materials: magnetic smart materials (MSMs) and shape memory alloys (SMAs). To date, we have shown a return to shape of 1 μm and that we can cause order 1 μm deflections with ~ 0.3 T imposed on the backing to the SMA. However, it will be much simpler to avoid the post deployment correction step, and a return to shape of 1 μm should be able to produce sufficiently small spot sizes as determined by the detector background (see § 4.2 below). Therefore, with new funding from NASA, we ~~could~~ segue the current work to demonstrate a technique for making deployable mirrors that reflect extreme ultraviolet at normal incidence. Such a capability, once executed, would allow exciting new EUV science to be carried out within a CubeSat or SmallSat budget.

3.1 The plan in brief

As we reiterate below, experiments are necessary to demonstrate if : (a) the eNiP plated NiTi can be made flat and smooth enough such that fully functional multilayers can be deposited; (b) the multilayers remain fully functional after a pseudo stow and deployment is accomplished; and (c) the inherent stiffness to the structure is not so significant that return to shape to $\leq$*1* μ*mis impossible; (d) the return to shape of a piece with fully functional multilayers is stable over days or weeks; and, (e) the structure of a test piece will be demonstrated to be mechanically stable to* $\leq$*1* μ*m over 2 years.*

4 Past 3 years results on using SMA for visible-light deployable optics

4.1 SMA work

The key points as the basis for our proposal are: (a)We have shown that return to shape of the tip of SMA on sheets 2 cm long can be done to 1 μ i.e. see Fig 2. We have plated the NiTi with high phosphorous content (13-15%) electroless nickel (eNiP hereafter) and polished it to an optical quality finish.

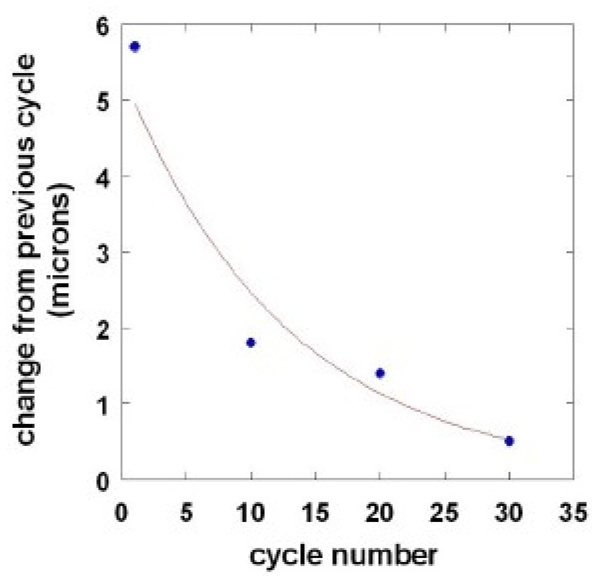


Figure 2: Demonstration of return to shape for a 2 cm long 100 μm thick sheet ~~to~~ NiTi.

4.2 Only 1 μm is needed

The~~m~~, in order to determine that interesting EUV astronomy can be carried out with a figure error commensurate with the return to-shape capabilities of the SMA, we carried out a ray tracing study.

We used a parabolic ~~a~~ mirror with a diameter and focal length of one meter. The spot size diameter that included 90% of the rays was sufficiently small, $< 500\,\mu$m. A spot size requirement of $< 500\,\mu$m is based on the expected background for a typical EUV-optimized micro-channel plate (MCP) detector [3]. The minimum background value in [3] is 0.25 cts cm^{-2} sec^{-1}, but to be conservative to calculate background, we use 0.5 cts cm^{-2} sec^{-1} which coverts to about 1E-3 cts sec^{-1} in a spot of 500 μm diameter. Thus, we conclude the fidelity of a shape set and trained SMA mirror will be sufficient to produce a telescope mirror that, when combined with a flight qualified MCP, will produce a mission measuring the flux from faint EUV source.

4.2.1 Lessons learned from surface finish work on eNiP plated NiTi in progress

We have already carried the first step the process making NiTi super-polished eNiP surface, which is to coat the NiTi with high phosphorous eNiP. The company used by MSFC, **North American EN, NAEN** produced for us a eNiP coating about 15 μm thick which Northwestern University students then polished to a visible-band mirror-like finish. Thus, we anticipate that professionals at MSFC will be able to produce a true super-polish finish as the have similar capabilities to those described in [5]. The preliminary results using Shack Hartmann Wave Front sensor (SHWFS) are very encouraging as show in Fig. 3

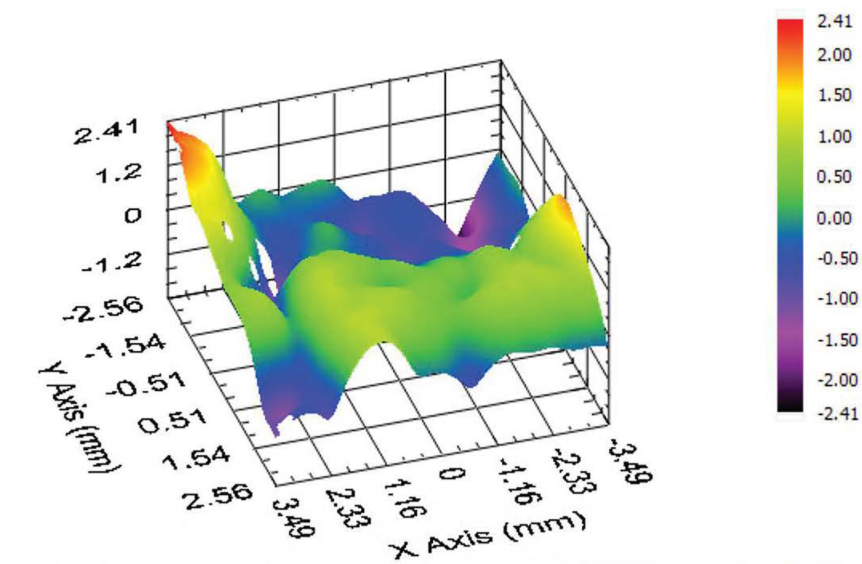


Figure 3: A SHWFS surface map of a~~n~~ $\sim$6 $\times$ 5 mm spot of 100 $\times$ 100 mm $\times$ 100 μm eNiP coated NiTi polished at NU.

The coating eNiP coating itself as carried out by NAEN has varied widely terms of the end product as we now described the proceeding paragraphs. The results act as justification as to why we plan to use customized eNiP coating for this project.

The plating process at NAEN begins with a Woods strike, which is a commercial chemical process designed to create adhesion between the substrate and the eNiP plating. On occasion, the adhesion has been good with no visible delamination, but other times the process failed. In the later case it is possible to remove the eNiP ~~without~~ with a 10% solution of nitric acid. The owner and CEO of NAEN reported that a poorly carried out Wood strike was the reason for the delamination.

Another problem that can occur is the plating stresses which can lead to unwanted figure distortion. Thus, for a test, we had three stainless steel feeler gauges eNiP plated on both sides to demonstrate that the plating stresses could cancel out. However, one of the ~~3~~, 82 mm long 100 μm thick feeler gauges in the same fixture and plated in the same run came out noticeably curved to the naked eye, i.e., a radius of curvature of about 0.5-1 m. The experience of varying outcomes from plating in the same bath and holder is another example of why moving to an in-house project is preferable to continued R&D work with a commercial firm.

5 Background information on shape memory alloys

Shape memory alloys (SMAs) are metallic alloys that can produce large strains (as high as 8 % in polycrystalline form) when subjected to changes in temperature or stress. These large strains arise from a martensitic transformation between lower and higher symmetry crystalline phases. The shape memory effect refers to an SMA that detwins when mechanically deformed in the lower symmetry phase. Upon heating, the lower symmetry phase transforms to a higher symmetry phase recovering the accumulated strain. The large strain (e.g., 8%) recovery associated with the shape memory effect in these alloys can occur against large stresses (e.g., 500 MPa), resulting in their use as actuators. Furthermore, if internal stresses bias the reverse transformation during cooling back to the lower symmetry phase, then strains can also be associated with this reverse transformation, a phenomenon called the two-way shape memory effect (TWSME). This effect is usually achieved by training the SMA specimen, i.e., cycling between its low temperature shape and high temperature shape [10]. Efforts in prototyping shape memory alloys actuators for space applications include thermal switches and re-deployable radiators for deep space spacecraft, among others [11, 12, 13, 14].

While SMAs have typically been used uniaxially in wire form, more recently they have been used multiaxially in beam and torque tube forms [15, 16]. SMAs are particularly advantageous for space-related applications in that: • They integrate sensory and actuation functions. The shape memory element when in equilibrium with the ambient temperature inherently senses a change in temperature and actuates by undergoing a shape change as a result of a phase transformation. Consequently, the need for external electronic sensors and control is eliminated. • They function in a clean, debris-less and spark-free manner. The shape change that is responsible for the actuator displacement is again an inherent material property. It is not associated with moving parts that require lubrication or electrical signals with a potential to spark. • They have high power/weight and stroke length/weight ratios. The operating range includes strain and stress limits of 8% and 500 MPa, respectively, depending on the number of required cycles. • They possess the ability to function in zero-gravity environments with small, controlled accelerations. The displacement strains are a result of a thermally-induced phase transformation which can be controlled by the heat transfer rate (e.g., appropriate insulation). • When compared to other metallic alloys, they offer superior energy storage densities when used for their SE behavior. For example, a standard steel spring can store about 5 MJ/m3 of energy while a SE spring can store 50 MJ/m3 due to the larger recoverable strains (8% vs 0.75%).

6 Previous NASA funded activities relevant to this proposal

6.1 SMAs

Alloying and thermomechanical processing of SMAs have been known to increase the phase transformation temperatures and improve their stability. NNX08AB51A Development and Characterization of High-Temperature Shape-Memory Alloys with in situ Neutron Diffraction Measurements at Temperature and Stress awarded to the Co-I by NASA Glenn Research Center built on that fundamental approach by additionally offering the following: (1) experimental and computational approaches that relied on novel in situ neutron diffraction measurements during heating/cooling and mechanical loading - to connect macroscopic behavior with atomic scale phenomenology not influenced by surface effects, under conditions identical to SMAs being used in high-temperature actuator applications; (2) a time and cost effective methodology that used arc-melting to melt centimeter-scaled button melts, subsequently cold-roll and heat treat the melts, and then mechanically and microstructurally characterize them - providing a way to first optimize processing parameters on small quantities of alloys prior to larger scale production; and (3) implementation of alloys in engineering prototypes relevant to high-force actuators and active/adaptive structures in turbine engines - emphasizing spring design, fabrication and testing.

The aforementioned general approach was specifically implemented through the following five tasks - fabrication, mechanical and microstructural characterization of high temperature shape memory alloys (HTSMAs); neutron diffraction during heating/cooling and loading at Los Alamos National Laboratory; modeling; prototype development with emphasis on spring design, fabrication and testing; and undergraduate and graduate student training at Los Alamos National Laboratory. Thus it facilitated the development of HTSMAs for use in high-force actuators and active/adaptive structures in turbine engines. The implementation: (1) provided unique insight into processing-structure-property correlations in HTSMAs by recourse to unique experimental and computational approaches, and used this insight to (2) establish a predictive methodology that reduces both the time and cost in developing HTSMAs while (3) improving the stability of these alloys with respect to their cyclic performance at high temperatures and high force levels.

NNX11AI57A: Subsonic Fixed Wing, NASA Fundamental Aeronautic Program: A Computationally-Efficient, Multi-Mechanism based Framework for the Comprehensive Modeling of the Evolutionary Behavior of Shape-Memory Alloysalso awarded to the Co-I through NASA Glenn Research Center with a focus on potential applications such as adaptive material for actuation devices for reshaping wing flaps, turbine nozzles, and fan or compressor blades, etc. Specifically, the work focused on the development of a computationally-efficient framework for modeling the evolutionary response of shape memory alloys (SMAs) under thermomechanical loads. To this end, a novel, multi-mechanism based, approach for SMA modeling, together with extensive sets of test results, including in situ neutron diffraction experiments at stress and temperature, for model validation and calibration was used. In particular, there were several unique contributions from the project: (i) on the modeling side, within the same framework, the comprehensive modeling capabilities of ordinary (mechanical and thermal response characteristics) as well as high temperature SMAs (with their significant degree of loading rates/time dependency) under general multi-axial conditions were combined; (ii) on the experimental side, the project addressed the following critical issues in SMA modeling: (a) linkage of experimentally observed micromechanical changes to such theoretical notions as internal state variables and their evolution; (b) identified critical experiments for calibration and characterization of general, multi-axial, SMA models; and (c) developed means to trace and visualize the transformation-induced limit/attraction surfaces in the subspaces of conjugate stresses and strains; (iii) on the computational side, developed a set of accurate and efficient algorithms for stress integration, and updating of cyclically evolving internal state variables, needed for large-scale simulations; (iv) on the fabrication and application side, the work theoretically identified and subsequently validated experimentally: (a) efficient routes for cyclic training of the SMA material systems; and (b) the greater potential afforded by using SMAs under multi-axial conditions in actuation devices.

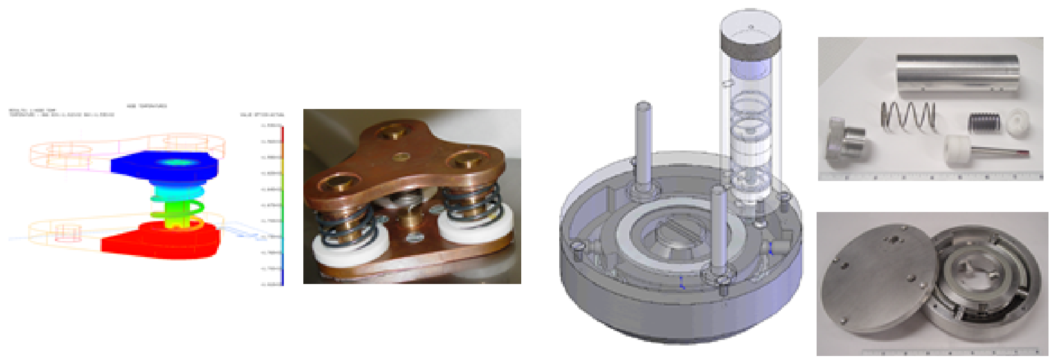


Figure 4: Projects involving shape memory alloys completed by the Co-I for NASA KSC that have resulted in US patents being issued. Design and implementation of shape memory alloys in a low temperature thermal conduction switch (US Patent No 7752866) (left two). Design and implementation of shape memory alloys in a release mechanism also for NASA KSC (US Patent No 8209976) (right two).

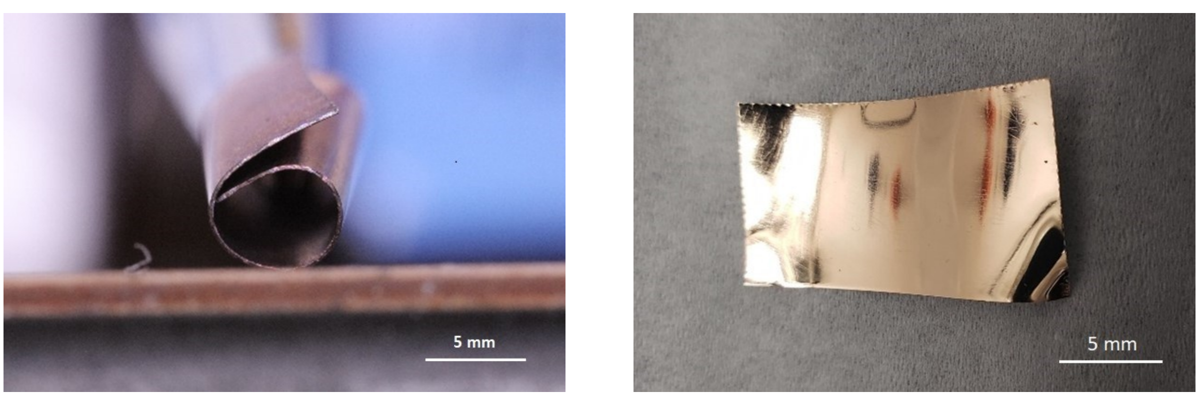


Figure 5: NiTi with Ti-Cu-Au sputtered layers after multiple cycles between the rolled configuration (left) and flat configuration (right).

6.2 Polished eNiP + CNx coating + multilayers for grazing incidence optics

The basic concept works in that we have shown that when eNiP is super-polished and then over coated with CNx, we can produce functional multilayers that reflective at about 8 keV at grazing incidence incidence[6]. However, polishing a rigid cylinder is much easier than polishing substrates that are only 100-500 μm thick.

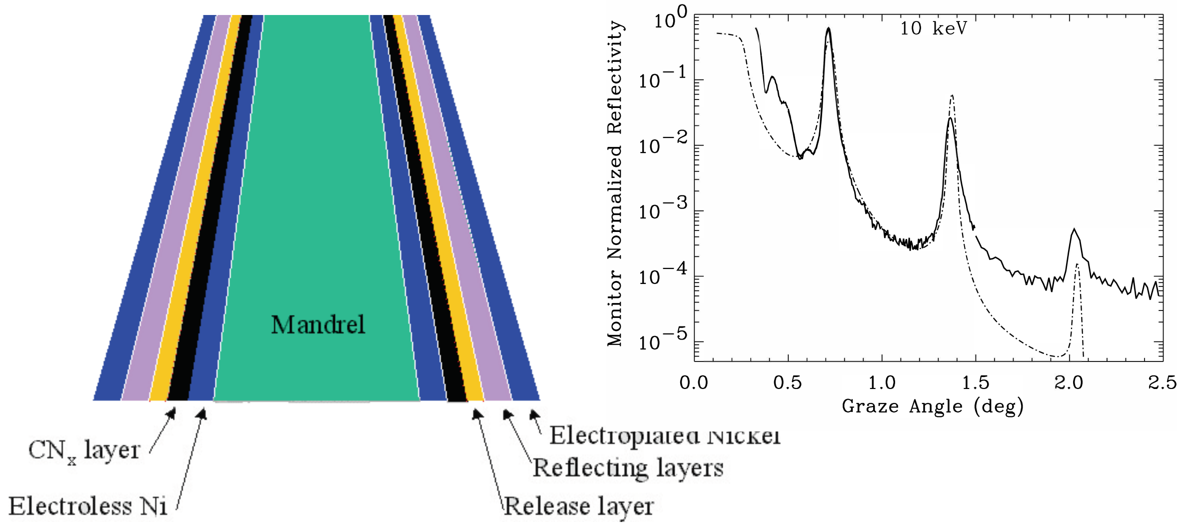


Figure 6: Left:Schematic of the mandrel and the principal coatings. The electroless-nickel-coated aluminum mandrel was supplied by Hyperfine Inc. of Boulder CO, produced a low cost *prototype* mandrel~~;)~~. All other coatings were deposited at Northwestern University. Right: The reflectivity at 10 keV vs graze angle on the mirror made from electroformed mirror made mandrel whose schematic is shown on the left. The solid curves show the experimental results. The dashed–dotted curves show the theoretical reflectivity for the model multilayer using IDL code (IMD) from David Windt.

Using a single-d-spacing of the deposited W/Si and the IMD model, we conclude that d-spacing of the W/Si multilayers were uniform to approximately 1% both around the cylindrical azimuth of the mirror and *as a function of depth*.

Effect that are likely to allow us to produce even a higher quality multilayers for the project proposed here are (a) the mandrel we used was a low cost proto-type and smoother surfaces from expert super polishers ~~is~~ possible. (b) The multilayers were removed from the deposition surface and a Cu release layer was dissolved off after removal. For the application here no release layer would be needed. The substrate upon which the mutilayers are to be deposited will act as the mirror substrate.

7 The plan

7.1 Proposed activities utilizing shape memory alloys sheet

As outlined previously, SMA sheet will be shape set and trained to a flat shape. This will enable it to be stowed in a rolled configuration in the martensitic state and open flat when heated as shown in Figure 5. A 100 μm thick sheet with an austenite finish temperature of 60 °C will be used. Prior to the shape set at 525 °C for 30 minutes, the sheet will be mounted and mechanically polished to an RMS surface roughness of about 80 nm, using SiC paper in multiple steps prior to a final polish using a 20 nm alumina suspension. This method has successfully been employed previously on a DoD project awarded to the PI and Co-I [17] can be trained flat. The training procedure is expected to modify a setup previously used in Ref [18]~~ef~~fig:Setup. It involves repeated heating, cooling and mechanical deformation cycles in an automated system. A laser confocal Keyence sensor will be implemented to ensure return to shape to within 1 μm following heating. The sheet will then be subject to electroless Ni deposition. The sheet thus trained and shape set will be subject to surface profilometry and microstructural characterization to correlate the variant structure with the training process. This will provide an understanding of the reflectivity of the overall sheet with the eNi, CNx and multilayers.

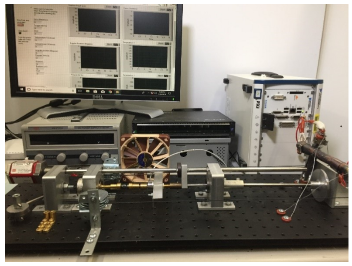


Figure 7: Setup used for training the shape memory sheet

7.2 Modeling

Two distinct tasks are detailed. The first task is to create numerical simulations for the multi-layer material structure. Our model of the multi-layered mirror will predict the material behavior of each layer and the complete mirror layers under the stowed and deployed configurations. The second task is to develop stowed configurations that incorporate NiTi hinges as actuators. Steps include creating metrics to quantitatively measure the potential benefit from incorporation of NiTi torsional tubes as a deployment mechanism/hinge. Several deployment configurations incorporating NiTi hinges will be modeled and simulations will be carried out using computer aided design (CAD) and finite element analysis (FEA) simulation software.

Regarding the second task, the entire timeline of the project is split into six steps.

Step 1: Perform a Literature search and review of current state-of-art to determine the optimal telescope/antenna model that would benefit from the incorporation of shape memory hinges. This task will also include the development of preliminary multi- physics simulations, including ray tracing, of the reviewed candidates. These simulations will act as a baseline from which comparisons will be made after integration of SMAs.

Step 2: Develop system requirements and a set of metrics to measure potential benefit from incorporation of SMAs. These metrics will include but ~~not be~~ limited to; structural capabilities of the SMA material to handle the expected loads, how close the simulated deployment configuration is to the ideal, potential areal density and weight savings from hinge incorporation, and resultant figure resolution after deployment.

Step 3: Select and characterize a set of materials based on requirements identified from Steps 1 and 2. Material selection and characterization will include SMA materials, reflective materials, and satellite casing/structure materials. Special attention to selecting materials with similar coefficient of thermal expansion will be made in order to minimize the effects of thermal cycling in space due to solar exposure and eclipse.

Step 4: Produce preliminary designs for the stowage and deployment configurations for an optical telescope making use of SMA into a 3U CubeSat. These preliminary designs would be based on the results of previous tasks. Metrics will be applied to these designs to down select a single solution.

Step 5: Produce a preliminary design of the SMA system. This system will include SMA configurations and shape memory triggering methods depending on material selection from Step 3 and CubeSat design development from Step 4.

Step 6: Synthesize a finalized overall design based on findings from Steps 4 and 5. The final step essentially entails running a multi-physics model simulating the installation of the final SMA system developed in Step 5 with the final CubeSat model developed in Step 4. The veracity of the design would be established based on the criteria identified in Step 2.

8 Work Flow and Task Description

The primary path of deploying sheets we propose is the sheet approach for two reasons: First, by working ~~we~~ sheets were are able to build off of previous work for normal incidence visible light mirrors. Second, carrying on two full-scale hard approaches simultaneously would require too many resources. However, there are design aspects of the hinge approach that overlap with the sheet concept. Thus there is synergy in budgeting a task that includes both the sheet and the hinges approach. Carrying out a design now is important for an overall proof of concept. Proof there is a viable stow and deployment design for a true mirror is necessary to justify further funding after carrying our what we anticipate will be successful first step with flats.

By institution

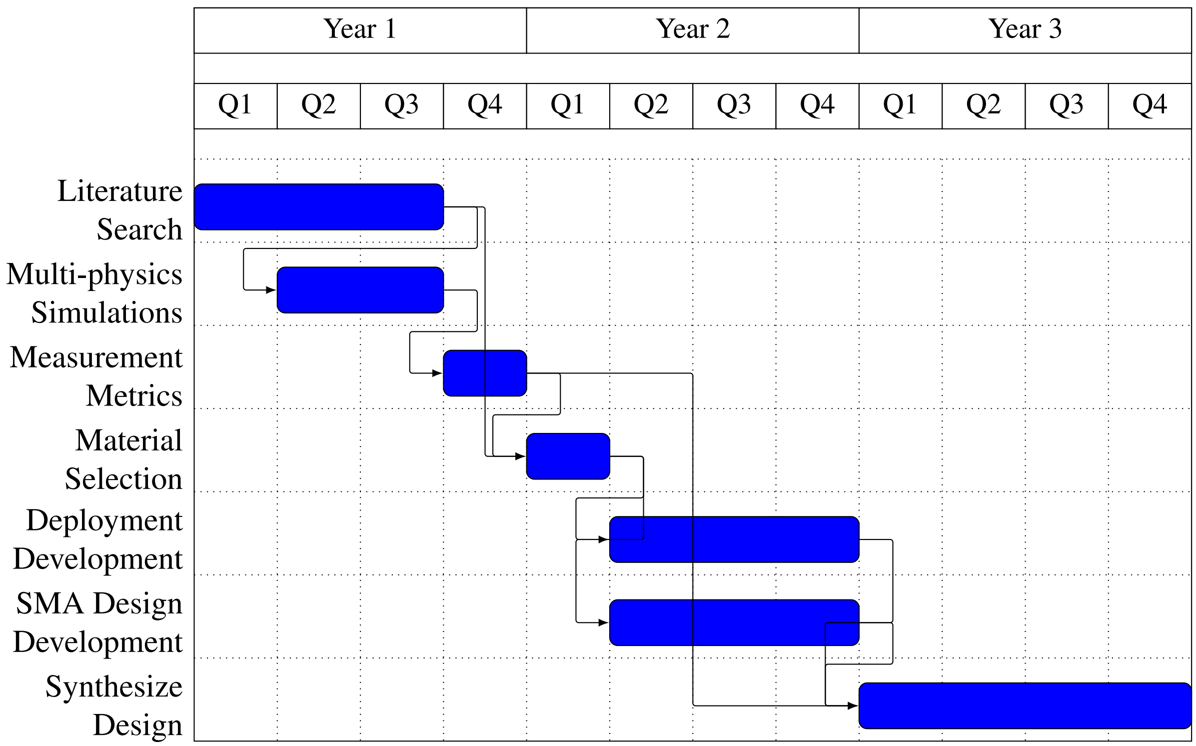
1. NU Overall Leadership and project management. CNx coating and multi-layer coating. Carry out the figure and surface metrology and the LBL EUV tests.
2. UCF carry ~~our~~ shape memory training of the flats.
3. U Miami Model provide compact designs that meet the requirements derived from the desired minimum spot size.
4. MSFC will: (1) carry out polishing of the eNi coated NiTi which is too thin to be coated by vendors. (2) They will also carry out ~~singel~~ point diamond turning pre-~~polihs~~ step to take out (3) carry out ray tracing to extend the preliminary ray tracing in order to determine how much the spot size ~~and~~ be diminished vs surface figure and focal length.
5. U Colorado advise on matching the EUV astronomy requirements with the figure our technology can produce.
6. GSFC will provide optical characterization of the multilayers and interferometer figure testing. GSFC wil also provide input on EUV astronomy requirements.
7. UNF will develop and carry out a low stress reliable eNiP coating technique.

9 Team Responsibilities and Expertise

After the PI all the rest are listed in alphabetical order

- PI Ulmer. Will be responsible for providing scientific leadership and overall project management. His relevant expertise to this project is that has experience in

9.0.1 Second Task Gantt Chart



10 Technical Risks and Mitigation

- Multilayer stability under elevated temperatures: The typical Mo/Si multilayer ~~is~~ especially designed for normal incidence EUV optics is stable at temperatures below $\sim 200^\circ$ C, but Mo_2C/Si multilayers are stable up 600°C [19]. In comparison, even the high T NiTi material-return-to-shape for deployment that we plan to use is about 130°C, and the low temperature version's return-to-shape temperature is about 60°C.

- Multilayers are not functional post deployment. Our backup plan is model a hinged design that uses a stiff substrate for the multilayers. Besides Si other possible substrates include Schott D263® and Zerodur®, or CESIC® which has good thermal conduction properties[20], and ~~that~~ can be machined[21].

- NiTi Stability. A stability test on a sheet will be carried out. A reset test will be carried out as well, i.e. even if the shape is not stable for years, a reset via heating should be possible. Furthermore, for the hinge option, the aerospace community has a vested interest in developing a stable actuator/hinge, e.g.[22]. Thus, hinge fall back design will be able to meet the stability requirement.

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12 Data Management Plan

No plan is necessary as this is technology development project.

13 Bio Sketches

14 Summary of Work Effort

Person and/or Role	Time Charged to this proposal	Time not charged to this proposal	Total Time per person/year
PI, Melville Ulmer	2 months/year	N/A	2 months/year
Co-I D. Bruce Buchholtz	1.1 months/year	N/A	2 months/year
Co-I Yip-Wah	0.25 months/year	N/A	0.25 months/year
Co-I Ron Shri	2.4 months/year	N/A	2.4 months/year
Co-I Mark T. Stahl	2.4 months/year	N/A	2.4 months/year
Postdoctoral Fellow	12 months/year	N/A	12 months/year
Graduate Student	12 months/year	N/A	12 months/year
Collaborator William Zhang	N/A	de minimis	de minimis
Collaborator Kevin France	N/A	de minimis	de minimis

15 Current and Pending

16 Letters of Support

17 Budget Narrative

18 Facilities and Equipment

19 Redacted Budget