Session 1602

Educational Methods/Aids Used in the Astronautics Core Course at the United States Air Force Academy

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Abstract

Every cadet at the United States Air Force Academy is required to take a one-semester course in astronautics based on the classic astronautics textbook, *Understanding Space*, by Jerry J. Sellers*, et. al.* The major sections of the course include orbital fundamentals, rocket fundamentals, and an introduction to space mission planning/operations. In addition to outside lecturers from the space operations community, teaching aids used in the course include the following:

1. Large and hand-held orbital elements models, ("whiz wheels") to illustrate orbital fundamentals;
2. Computer-based demonstrations such as STK to illustrate orbital characteristics;
3. Full-size examples and models of past and present satellites and rockets and their subsystems;
4. A demonstrational micro-satellite that has fully functional compartmentalized subsystems.

The micro-satellite is particularly helpful in illustrating the physical concepts, components, and functions of each subsystem of a satellite. This paper discusses the contents and teaching methods/aids used in this undergraduate course on the fundamentals of astronautics.

I. Introduction

About half of the courses taken by every cadet at the United States Air Force Academy (USAFA) are made up of required specific core courses including at least one course from every one of the 19 departments at the Academy. The core course required in the Astronautics Department is Astro 320, Introduction to Astronautics for the Engineer and Scientist, a course required for technical majors, or Astro 410, Introduction to Astronautics, for non-technical majors. In Astro 410, the textbook is *Understanding Space: An Introduction to Astronautics*, by Jerry J. Sellers, *et.al*. (USIA)[1]. The main difference in the courses is that in Astro 320 for engineers, *Fundamentals of Astronautics* by Roger R. Bate, *et.al*. is used as a textbook in addition to USIA, and there are problems requiring programming in MATLAB[2]. The cadets in Astro 320 are also required to write three reports to accompany their programming and design projects. The difficulty in the solutions of problems is at a higher level in Astro 320. Most of the teaching aids are generic to both courses. The syllabi for both courses are included in Appendix A.

This paper will concentrate on the teaching aids used in both courses:

1. Large and hand-held orbital elements models, ("whiz wheels") to illustrate orbital fundamentals;
2. Computer-based demonstrations such as STK to illustrate orbital characteristics;
3. Full-size examples and models of past and present satellites and rockets and their subsystems;
4. A demonstrational micro-satellite that has fully functional compartmentalized subsystems.

The micro-satellite is particularly helpful in illustrating the physical concepts, components, and functions of each subsystem of a satellite.

II. Textbook

The greatest teaching aid at the United States Air Force is the primary textbook, *Understanding Space: An Introduction to Astronautics* by Jerry J. Sellers, *et.al*. This great textbook is written totally from a teaching standpoint for the teacher and a learning viewpoint for the student. Illustrations are used extensively to visualize the concepts. Example problems are worked step-by-step both using mathematical symbols and with numbers. Thorough summaries are provided at the end of each section. This text makes a complex subject as understandable as possible.

III. Orbital Fundamentals

The fundamentals of astronautical orbital mechanics are based on the six classical orbital elements (COEs) with reference to an inertial coordinate system. For orbits around Earth, the inertial coordinate system is based on a right-hand coordinate system with:

1. The fundamental plane being a plane passing equator of the earth.
2. The basis vectors are such that the principal direction, I, is pointing toward the vernal equinox.
3. Using a right-hand coordinate system such that K is passing away from the fundamental plane through the North Pole.

This inertial coordinate system is referred to as the geocentric-equatorial coordinate system because the center of the earth is the origin and the fundamental plane passes through the equator. Using this coordinate system as a reference, the six classical orbital elements are defined. Although they are actually mathematically defined, the verbal definition is given below[1].

1. The semimajor axis, a, is a measure of the size (mechanical energy) of the orbit.
2. The eccentricity, e, is a measure of the shape of the orbit.
3. The inclination, i, is the angle that measures the tilt of the orbital plane with respect to the equatorial plane.
4. The right ascension of the ascending node, Ω, is the angle measured from the principal direction (vernal equinox) in a right-hand direction (eastward) along the equatorial plane to the point at which the satellite crosses the equator going from the Southern Hemisphere to the Northern Hemisphere.
5. The argument of perigee, ω, is the angle measured along the orbital path in the direction of the satellite's motion from the right ascension of the ascending node, Ω, to the perigee of the orbit, (Perigee is the position on the orbit where the satellite is closest to the Earth.)
6. The true anomaly, ν, is the angle measured along the satellite's orbital path, in the direction of the satellite's motion, from perigee to the satellite's position.

To add to the student's confusion is the fact that three alternate COEs occur under certain conditions, which will not be discussed here. The values of the COEs also determine whether the orbit is circular, elliptical, parabolic, hyperbolic, direct, indirect, geostationary, etc. Visual aids are an absolute necessity to aid the teaching of these concepts.

IV. Whiz Wheels

One great visual teaching aid is the use of orbit element models, sometimes referred to as "whiz wheels". The classroom version of the whiz wheel is shown in Figure 1. This device has the capability of demonstrating the following:

1. The physical characteristics of the COEs including how they are measured relative to the principle axes and fundamental plane of the geocentric-equatorial coordinate system, and in which direction the COEs are measured.
2. The effect that change in the values of the COEs will have on the orbit.
3. The resulting ground tracks caused by the earth rotating on its axis under the orbit fixed in space.

Whiz wheels have been used in the Astronautics Department at the Air Force Academy for over 20 years and were particularly helpful before the excellent computer-generated aids now available. Each cadet is given a construction kit for a hand-held whiz wheel. See Figure 1. The instructions for building one from a kit appears in Appendix B. The actual construction must be of cardboard to give it some rigidity. Students are allowed to use their hand-held whiz wheels on all examinations, including the final examination.

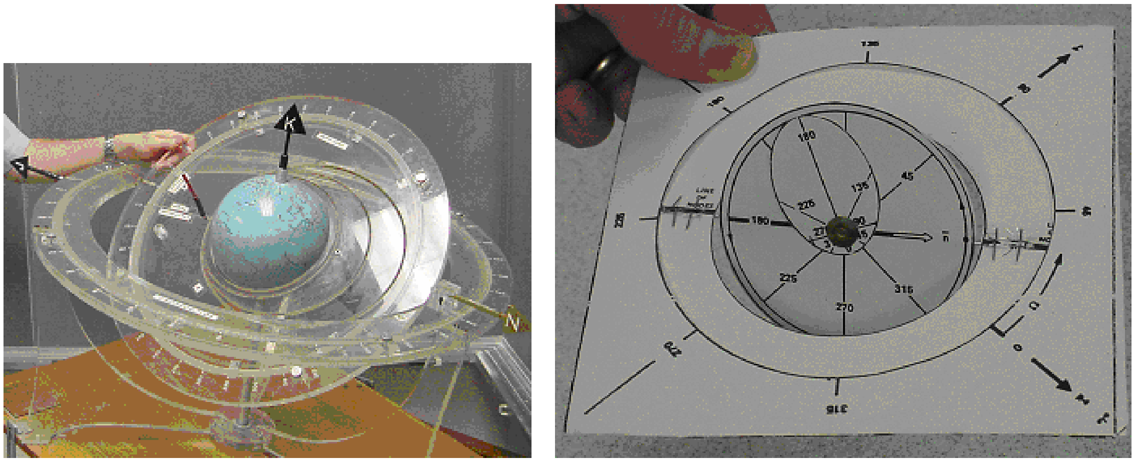


Figure 1. Classroom and Hand-Held Orbital Elements Models ("Whiz Wheels").

V. Computer-Based Orbital Demonstrations

Since students love video games, the current surge in computer programs that generate orbits of any size, shape, and mission are a great addition to the visual teaching aids in astronautics. Satellite Tool Kit (STK), by Analytical Graphics, Inc. is well known, but others exist[3]. With the intense competition in this field, the appearance of programs that concentrate on being more and more user-friendly is certain to make this a major part of teaching astronautics at all levels. Of course the ability to watch the satellite go round and round in its orbit is the first draw for the student, but the versatility of these programs to view the orbit in both two and three dimensions from various viewing positions is incredibly helpful to the student. The ability to view Earth from the satellite and the use of a cone of light to illustrate swath widths on Earth, are just the beginning of the visual illustrations possible. The most dramatic visualization is the effect of changing the values of the COEs. Changing the eccentricity from zero for a circular orbit to 0.8 for a highly elliptical orbit, immediately conveys the effect of eccentricity. The effect of this change of value of eccentricity on ground tracks can also be instantly demonstrated. Why the Molniya orbit has its characteristic ground track can be quickly illustrated. The effect of the argument of perigee on ground tracks can also be quickly demonstrated. The computer-generated demonstrations of orbital characteristics will only increase in importance as an aid in teaching astronautics in the future.

VI. Full Sized Examples of Satellites, Rockets, and Their Subsystems

The Air Force Academy is privileged to have full sized examples of satellites, rockets and their subsystems in both the Astronautics Museum and outside displays. A full sized Minuteman III ICBM stands in front of the field house, a stone's throw from the academic building. A full sized Defense Satellite Communications System II (DSCS II), housed in the Astronautics Department Museum, is a great example to show that satellites are not necessarily small. See Figure 2. The museum also has many scale models of various missiles and satellites, as well as full-size guidance and control systems from many missiles, satellites, and aircraft.

The ability for the student to see and feel satellites and missiles makes the course more realistic, not just a star wars fantasy. The cadets also realize that Astronautics majors work on a capstone project to either build a satellite that is launched into space (FalconSAT) or build a rocket that is launched to the edge of space (FalconLAUNCH). Except for the launches, both of these programs are conducted by cadets at the Air Force Academy. See Figure 3. Refer to *Student Design, Development and Operations of Small Satellites at the United States Air Force Academy* by Siegenthaler, *et.al*. for a more complete description of the FalconSAT program[4]. Figure 4 shows the inside of the FalconSAT Ground Station for controlling the satellites of the FalconSAT program while they are in space. This station is manned by cadets who want to participate in the FalconSAT Program. A full discussion of the training and operations program of the FalconSAT Ground Station crews is presented in *Spacemanship at the United States Air Force Academy: Developing a Satellite Ground Station Crew-Training Program for Non-Technical Students* by Swanson, *et.al*[5]. Figure 5 is an illustration of an early rocket built and flown by cadets to demonstrate the feasibility of hybrid rocket motors. Figure 6 shows the setup of a demonstration for students of how hybrid rocket motors work using oxygen and Plexiglas. Being surrounded by items and activities that are space oriented is a very positive teaching aid for astronautics.

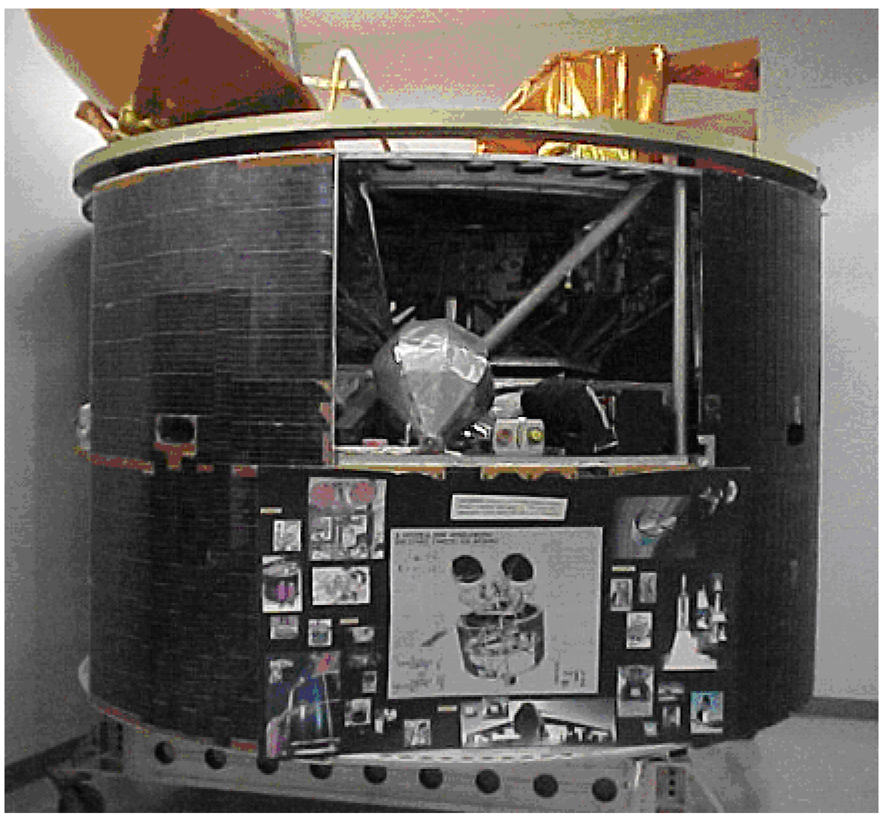


Figure 2. A Full Size DSCS II in the USAFA Astronautics Department Museum

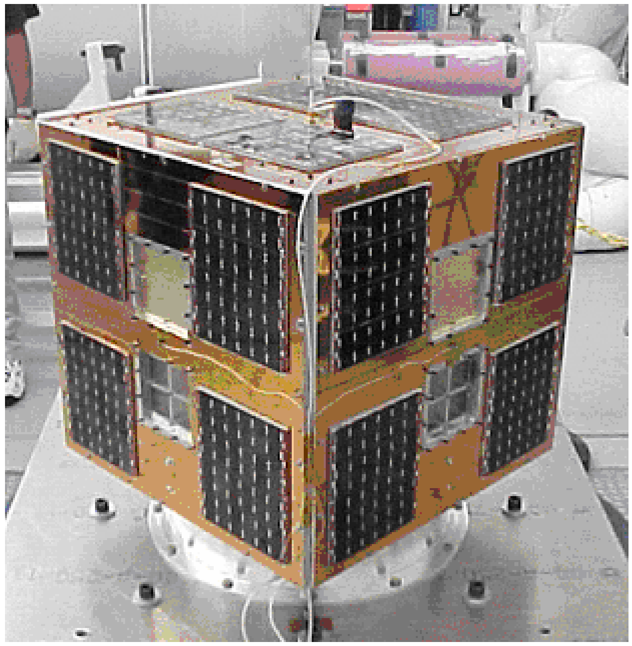


Figure 3. FalconSAT-1

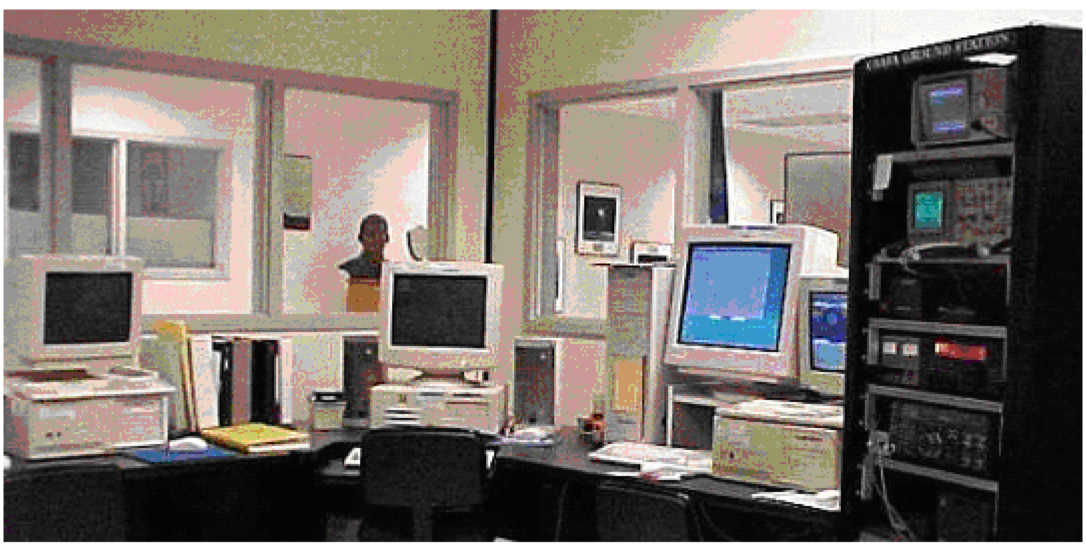


Figure 4. FalconSAT Ground Station

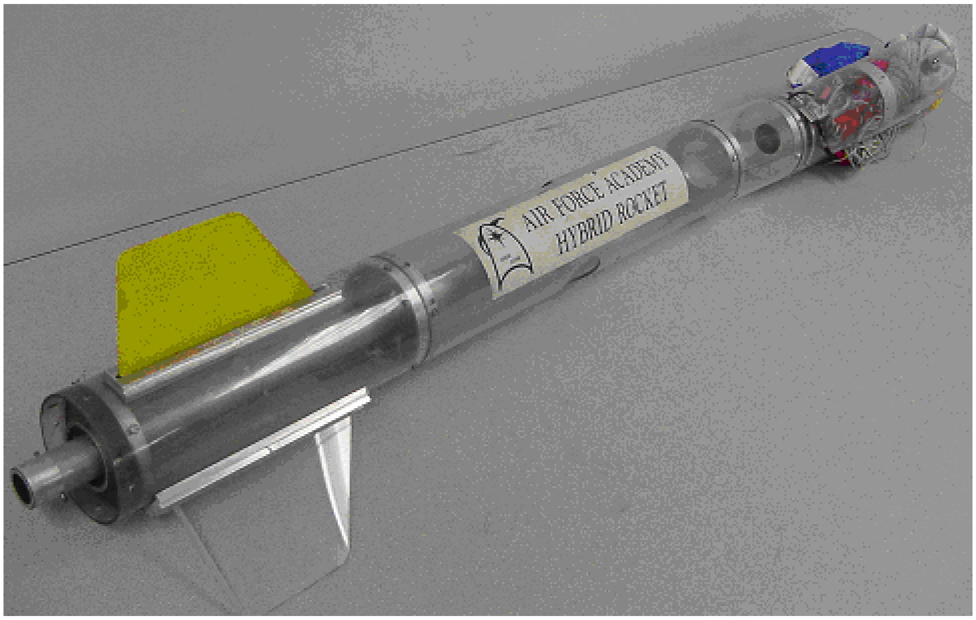


Figure 5. Rocket Built by United States Air Force Academy Cadets to Demonstrate Feasibility of Hybrid Rocket Motors.

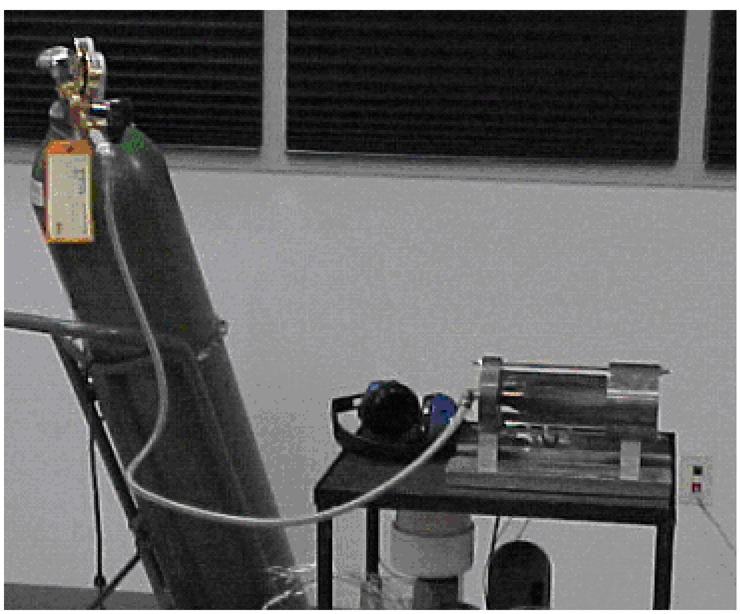
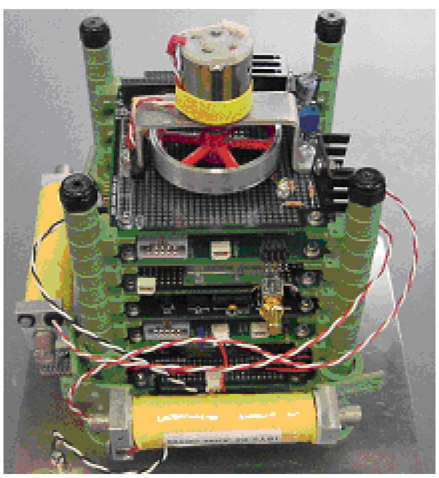


Figure 6. A Hybrid Rocket Motor Demonstration of Oxygen and Plexiglas.

VII. Micro-Satellite Demonstration of Subsystems

A major part of Astro 320 and Astro 410 is a design exercise of a satellite to be flown on a remote sensing mission. After the payload and orbit are determined, a major portion of the project is the design of the subsystems of the bus. A new teaching aid is a micro-satellite built at the Air Force Academy named EyasSAT[6]. Eyas means "baby falcon". (The falcon is the Air Force Academy mascot, so the satellite program where cadets build satellites to launch into space is called FalconSAT. Therefore, this micro-satellite built as a teaching aid on a smaller scale is named EyasSAT.) EyasSAT is constructed in modular form with each subsystem forming another module. It is fully functional to demonstrate the operation of the various subsystems by hanging it by a wire from the ceiling and remote controlling the satellite on a wireless system from a computer. One of the main advantages is that each subsystem is an independent module, so each subsystem can be taught so the student can visualize and put in its proper perspective that subsystem in relation to the rest of the satellite. Figures 7 and 8 demonstrate the modular nature of EyasSAT. The Attitude Determination and Control Subsystem (ADCS) consists of a reaction wheel and magnetic torque rods. The Electrical Power Subsystem (EPS) consists of solar panels and rechargeable batteries (See Figure 8). Refer to *EyasSAT: Transforming the Way Students Experience Space Systems Engineering* by Barnhart, *et.al*. for a more complete description of EyasSAT and its teaching role in many of the Astronautics Department courses[7].



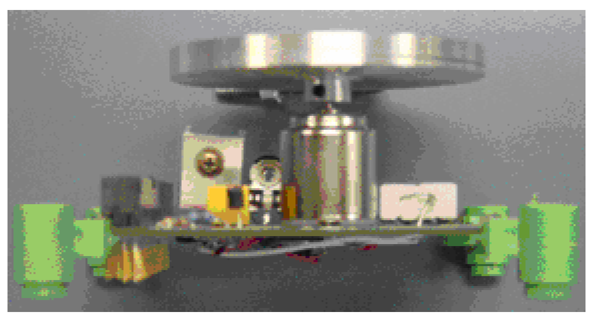


Figure 7. The Modular Construction of EyasSAT, with the ADCS Module on the Right.

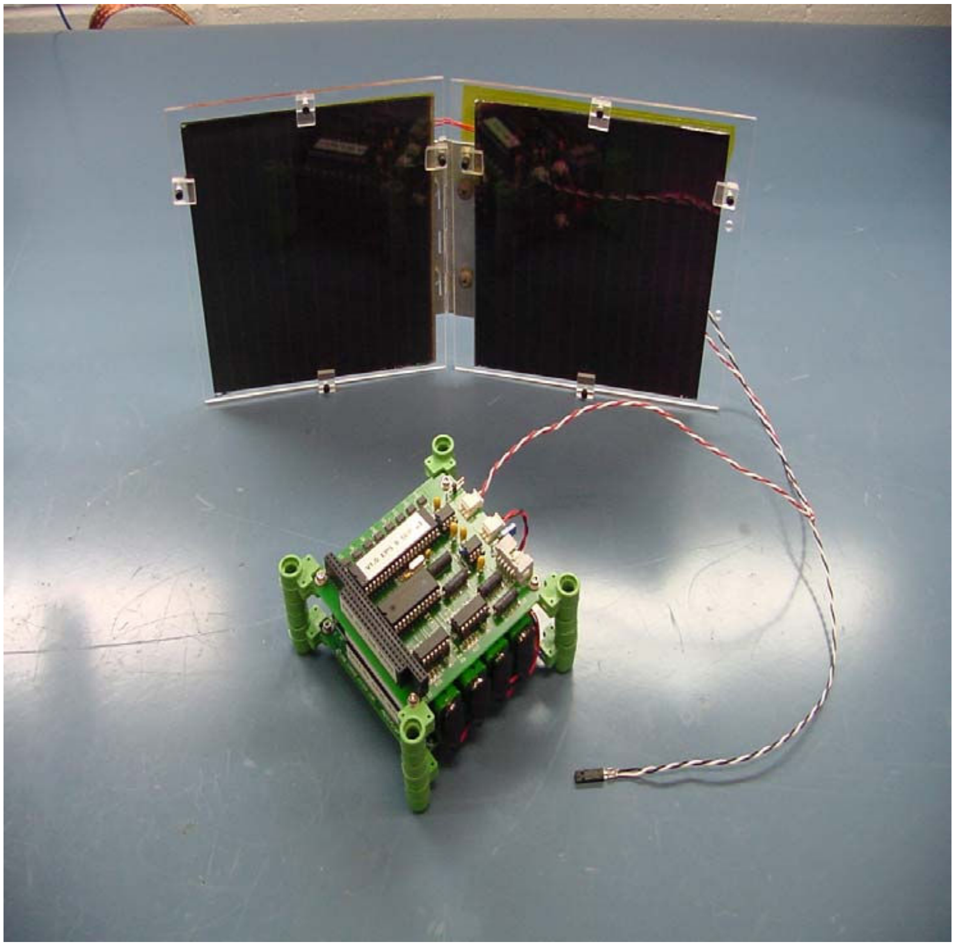


Figure 8. The Integrated EyasSAT EPS

VIII. Conclusions

The motto in the Department of Astronautics at the United States Air Force Academy is "Learning Space by Doing Space". Every effort is made to expose cadets to as many space related objects and activities as possible. It is like learning a language while living in a country where you are forced to use it all the time. Astronautics is taught with many modern aids to ensure that the student can relate to some aspect of space. Some cadets like rockets because they make a lot of noise and have high thrust. Some cadets like the challenge of the complexity of launching a satellite into space. Because the future of the Air Force is in space, the Astronautics Department has a heavy responsibility to run the best astronautics teaching program possible to properly train and prepare every cadet to meet that challenge.

IX. Acknowledgements

The authors would like to acknowledge the contributions of Mr. John Clark, Master Sergeant Phil Maes, Technical Sergeant Chad Bruce, and Technical Sergeant Benjamin Hazen. If you enjoyed reading this paper, credit our editors, Dr. Fred Kiley and Ms. Lynnette Kaffine.

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3. *Introduction to Satellite Tool Kit: Training Manual*, Analytical Graphics, Inc., Malvern, PA, 2001.
4. Siegenthaler, Kenneth E., Jerry J. Sellers, David J. Richie, and Timothy J. Lawrence, "Student Design, Development and Operations of Small Satellites at the United States Air Force Academy," *Proceedings of the 2004 American Society for Engineering Education Annual Conference & Expositio*n, Salt Lake City, UT, 20-23 June, 2004.
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7. Barnhart, David J., Obadiah Ritchey, Jerry J. Sellers, James J. White, and Tim White, "EyasSAT: Transforming the Way Students Experience Space Systems Engineering," *Proceedings of the 2004 Annual American Society for Engineering Education Annual Conference & Exposition*, Salt Lake City, Utah, 20-23 June, 2004.

Biographies

KENNETH E. SIEGENTHALER is an Associate Professor of Astronautics at the U.S. Air Force Academy. Dr. Siegenthaler has a B.S in the Arts & Sciences from the U.S. Military Academy, a B.S. in Physics from the University of Utah, and a M.S. and a Ph.D. in Engineering Physics from the Air Force Institute of Technology. He is a registered Professional Engineer in the state of Colorado.

DAVID J. BARNHART is an active-duty Captain in the United States Air Force and an Assistant Professor of Astronautics and FalconSAT-2 Program Manager at the U.S. Air Force Academy. Capt Barnhart has a B.S. in Electrical Engineering from Oklahoma State University and an M.S. in Electrical Engineering / Space Electronics from the U.S. Air Force Institute of Technology. He is a registered Professional Engineer in the state of Oklahoma.

JERRY J. SELLERS is an active-duty Lieutenant Colonel in the U.S. Air Force and an Associate Professor of Astronautics at the U.S. Air Force Academy. He has a B.S. from the U.S. Air Force Academy, M.S. from U. of Houston, M.S. from Stanford University and a Ph.D. from the University of Surrey, UK. He is the Director of the USAF Academy Space Systems Research Center in Colorado Springs, CO.

JAMES J. WHITE has extensive experience in the space community. His present interest is mainly in the design, fabrication, and operation of nano-satellites and micro-satellites.

TIM WHITE has a B.A. from the University of Colorado at Boulder. His expertise is in computer software and hardware development.

APPENDIX A
ASTRONAUTICS 410
INTRODUCTIN TO ASTRONAUTICS
Syllabus: SPRING 2004

Less on	Subject	Reading	Mission Problems	Assignments Due
1	Admin/Course Introduction Air Force Space Systems—The Space and Air Force?	Electronic Presentation/ Chapter 1	1,4,11	
2	Exploring Space	Chapter 2, Appendix A	1,9,14,15	
3	The Space Environment	Chapter 3	1,6,17,19	***Skills Review/ Student Survey***
4	Design Project Intro/Payload and Spacecraft Design	Chapter 11.1	1,3,7	
5	Remote Sensing	Chapter 11.2	17,24	
6	Understanding Orbits: Basic Laws (Kepler and Newton)	Chapter 4.1-2	1-3,6,10,13,15	
7	Understanding Orbits: Restricted 2-Body Equation of Orbital Motion and Orbital Constants (ε and $\mathbf{h}$)	Chapter 4.3-5	17,20,22-23,28	
8	Describing Orbits: Orbital Elements (Definition)	Chapter 5.1	1,5	***Design Project: Part I***
9	Describing Orbits: Orbital Elements (Computation)	Chapter 5.2	10,15,16	
10	COE Review and Introduction to Ground Tracks (I)	Chapter 5.3	20-21	
11	Describing Orbits: Satellite Ground Tracks (II)	Chapter 5.3	22-23	
12	Maneuvering in Space: Hohmann Transfers	Chapter 6.1	1-3,5	
Less on	**Subject**	**Reading**	**Mission Problems**	**Assignments Due**
13	Maneuvering in Space: Plane Changes (Simple/ Combined)	Chapter 6.2	6,8,10,12	
14	Maneuvering in Space: Rendezvous (Co-orbital and Non-Co-orbital)	Chapter 6.3	13-15	
15	Interplanetary Travel: Equation of Motion/Patched Conic Approximation	Chapter 7.1	1-5	
16	Interplanetary Travel: Equation of Motion/Patched Conic Approximation	Chapter 7.2	7,9-10	***Design Project: Part II***
17	Interplanetary Travel: Gravity Assist and Wrap-Up	Chapter 7.3	13-15	

18	Review			
19	**MID TERM**	**Chapters 1-7, 11**		
20	Mid Term Review			
21	Predicting Orbits: Kepler's Problem	Chapter 8.1	2,4,5	
22	**Predicting Orbits: Orbit Perturbations + Real World Prediction Problem**	Chapter 8.2-3	6-11	
23	Special Topics/Guest Speakers			
24	Spacecraft Subsystems: Control Systems/Attitude Control	Chap 12.1-2	2,4,10,11,15-27	
25	Spacecraft Subsystems: Orbit Control	Chap 12.3	28,29,31-33	
26	Spacecraft Subsystems: Data Handling	Chap 13.1	1,5,8,11,13	
27	Spacecraft Subsystems: Electrical Power Systems	Chap 13.2	15,21,23,24	
28	Finish EPS, In Class Design Project Time	Chap 13.1-2	25,29	
29	Spacecraft Subsystems: Environmental Control, Life Support, and Structural Systems	Chap 13.3-4	37-41,45-48,53	
Lesson	**Subject**	**Reading**	**Mission Problems**	**Assignments Due**
30	Finish TCS, In Class Design Project Time	Chap 13.3-4	57-58,60,65,67,71	
31	Spacecraft Subsystems: Communications	Chapter 15.1	1,5,19	
32	Air Force Space Operations	Elec Pres/ Chap 15.2	20,25	
33	Getting to Orbit: Launch Windows and Time	Chapter 9.1	1,3,5-8	***Design Project: Part III***
34	Getting to Orbit: When and Where to Launch	Chapter 9.2	9-10,12-14,17	
35	Getting to Orbit: Launch Velocity	Chapter 9.3	20-24	
36	Space Transportation Systems: Rocket Basics	Chapter 14.1	1,3-4,7-12,24,26	
37	Space Transportation Systems: Systems	Chapter 14.2	30,40,44,48,50	
38	Space Transportation Systems: Staging	Chapter 14.3	68-69,71	
39	Air Force Launch Vehicles	Electronic Presentation		
40	Returning from Space: Trajectory Design Options	Chap 10.1-2	1-3,6-8,10	***Design Project: Part IV***
41	Returning from Space: Vehicle Design Options	Chapter 10.3-4	15-16,19	
42	Review	Chapter 16		
Final	**Final Exam**	Chapters 1-16		

		Astro 320 Syllabus			**Spring 2004**
Block of Material	**LSN**	**Topic**	**Reading**	**Homework**	**Work Due**
Exploring Space/ Space Environment	1	Course Intro, Why Space? Exploring Space	Student Coursebook, US Appx A, Ch 1, 2	**US 1**: 1,3,11 **US 2**: 1,5,14-15	
	2	Finish Exploring Space, Space Environment	US 3.1-3.3	**US 3**: 4-7, 11, 13, 16-17, 19	Student Info Sheets
Orbits	3	Basic Laws, Coordinate Systems	US 4.1-4.3, BMW 2.2	**US 4**: 1-3, 9, 11, 13, 17	**Skills Review** *MATLAB HW #1*
	4	2-Body Problem, Orbital Geometry	US 4.4, Appx C.1,C.3 BMW 1.5-1.10	**US 4**: 19-21, 23	*MATLAB HW #2*
	5	Constants of Motion	US 4.5, Appx C.2 BMW 1.4	**US 4**: 24-25, 27-28, 30	*MATLAB HW #3*
Programming	6	Project Intro: Computer Problem Solving Debugging Techniques			*MATLAB HW #4*
Orbits	7	**C**lassical **O**rbital **E**lements	US 5.1	**US 5**: 1, 3, 6, 7	*Project Intro Algorithm*
	8	COEs from **R** and **V**	US 5.2, Proj Astro Description	**US 5**: 10, 14, 16-17 **MS1** Case#2 Hand Calcs	*MATLAB HW #5*
	9	Whiz Wheel Instruction, Good Morning Lt Exercise			*Project Intro*
	10	Ground Tracks	US 5.3	**US 5**: 19-23	
Programming	11	Project Astro Part I (Algorithm Development)	Project Astro Description	*Coding Part 1*	
Orbits	12	Orbit Prediction	US 8.1, BMW 4.1,4.2.1	**US 8**: 2-5	**Proj Astro Part I Algorithm**
	13	Orbit Perturbations	US 8.2	**US 8**: 6-7, 10	
	14	Predicting Orbits in the Real World	US 8.3	**US 8:** 11	***Proj Astro MS 1***
	15	**R** and **V** from COEs	BMW2.2.4, 2.5, US Appx C.7		
	16	Coordinate Transformations, Newton's Iteration Method	BMW 2.6,4.6.4 US Appx C.7	**BMW** 2.8	
Reinforcement/ Evaluation	17	Review / Catch-up			**Project Astro Part 1**
	18	**Mid-Term GR**		*Review*	**Graded Review**

US - *Understanding Space:* BMW - *Fundamentals of Astrodynamics* -Bate, Mueller, White					
Programming	19	GR Discussion / Part II Algorithm Development	Proj Astro Description	Proj Astro Part II Case #1 handcalcs (new true anomaly, **R** & **V**)	
Maneuvering in Space	20	Hohmann Transfers	US 6.1	**US 6**: 1-5	**Proj Astro Part II Algorithm**
	21	Plane Changes	US 6.2	**US 6**: 6-12	
	22	Rendezvous	US 6.3	**US 6**: 13-15	
	23	ISpecial Topics: Guest Speaker			
	24	Planning for Interplanetary Travel	US 7.1-7.2	**US 7**: 2, 4, 6, 7	***Proj Astro MS 2***
	25	Patched Conic Approx	US 7.2	**US 7**: 8-10	
	26	Gravity-assist Trajectories	US 7.3	**US 7**: 12-15	
Spacecraft Subsystems and Design	27	Design Project Intro, Payload and Spacecraft Design	US 11.1, Design Project Description (Lab Tour)	**US 11**: 3, 4, 7	**Project Astro Part II**
	28	Remote-Sensing Payloads	US 11.2	**US 11**: 14, 18-19, 22, 24	
	29	Space Vehicle Control Systems--ADACS	US 12.1-12.2	**US 12**: 1, 8-11, 15-16, 20-22, 25, 27	
	30	Orbit Control--NGC, Data Handling	US 12.3, US 13.1	**US 12**: 28, 29, 31 **US 13:** 13	***Design Project Milestone 1***
	31	Electrical Power System (EPS)	US 13.2	**US 13**: 15, 21, 23-30	
	32	Thermal Control System & Life-Support, Structures	US 13.3-13.4	**US 13**: 38-41, 45, 49, 51, 57-60, 65-66	
	33	Communication & Space Operations	US 15.1-15.2	**US 15**: 8, 11, 16-17, 20	
	34	Design Project	Design Project Description		
Getting To and From Space	35	Launch Windows and Time	US 9.1	**US 9**: 1, 3-8	***Design Project Milestone 2***
	36	When and Where to Launch	US 9.2	**US 9**: 12-14, 17	
	37	Launch Velocity	US 9.3	**US 9**: 20-23, 25	
	38	STS: Rocket Basics	US 14.1	**US 14**: 1, 3, 7-11, 17,	
	39	STS: Propulsion Systems & Staging	US 14.2, 14.3	**US 14**: 25-26,30, 32, 44-45, 48-50, 58	
	40	STS: Launch Vehicles & Re-Entry	US 10.1-10.2	**US 14**: 68-71	**Design Project Final**
	41	Finish Re-Entry	US 10.3-10.4	**US 10**: 1-4, 6-7, 10, 15-17, 19-20	
	42	Course Review	*Course Review*		

APPENDIX B
CONSTRUCTION OF HAND HELD ORBITAL ELEMENTS MODELS

ORBITAL ELEMENTS MODEL
Assembly Instructions

I. Cut out Parts A, B, C, D, and E (See Fig . 1). Take extra care to ensure that the outer rim of part A is perfectly smooth and circular so that it will rotate freely inside part E.

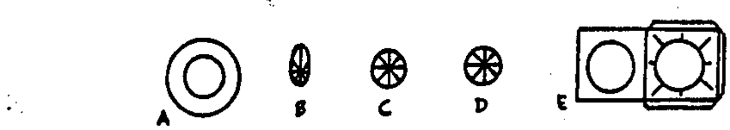


Figure 1

II. Bend two paper clips as shown in Fig. 2 and tape them to the back (blank) side of part C. The straightened part of the clips should line up with the $\bar{n}$ vector and stick out 5/8 inches past the rim of part C. (Make sure the clips are taped securely and line up to form a single axis aligned with the $\bar{n}$ vector.)

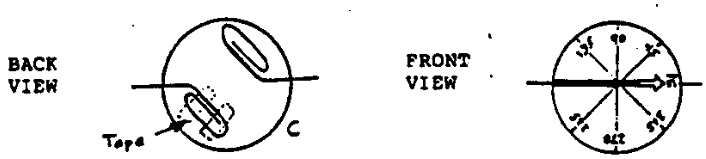


Figure 2

III. Glue part D onto the back of part C so that the numbers on each face line up. Press the two parts together so that they form a sandwich with the paper clips in between. (See Fig. 3).

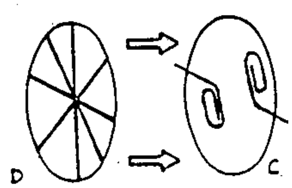


Figure 3

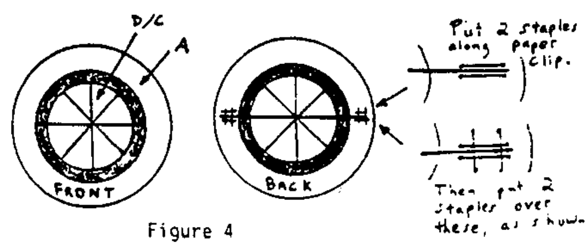


Figure 4

IV. Place assembly D/C inside the hole in part A so that the $\bar{n}$ vector on D/C lines up with the line of nodes on A and both point in the same direction. Tape the ends of the paper clips to the BACK side of part A. (Place staples on each side of each paper clip where they are taped to part A. This is to keep the clips from sliding under the tape out of alignment with the line of nodes. (See Figure 4.)

V. Rotate assembly D/C about its paper clip axis until it is coplanar with part A and the arrow at the ascending node on D/C points counterclockwise. (See Fig. 5). Fasten part B through its focus to the center of assembly D/C using a thumb tack and a uniform insignia "frog".

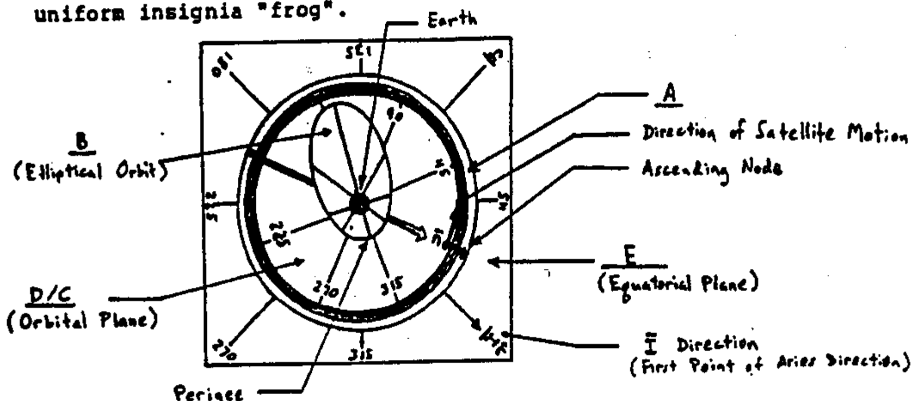


Figure 5

VI. Assemble envelope E. Insert assembly A/B/C/D into the envelope so that the lettering on both parts faces in the same direction. MAKE SURE IT WILL ROTATE SMOOTHLY INSIDE THE ENVELOPE BEFORE SEALING THE ENVELOPE! ..You may need to smooth the outer rim of part A to get it to turn freely in the envelope.

VII. Sit back and admire your new orbital elements model!

IX. Using Figure 5 and the definitions of orbital elements, found in Chapter V of the text, practice using the model. Try this example:

$$i = 30^\circ$$

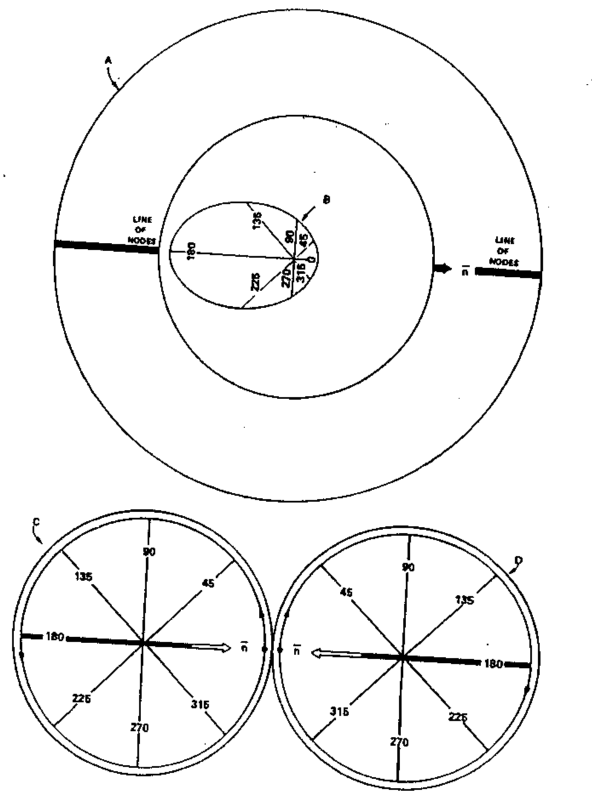
$$\Omega = 180^\circ$$

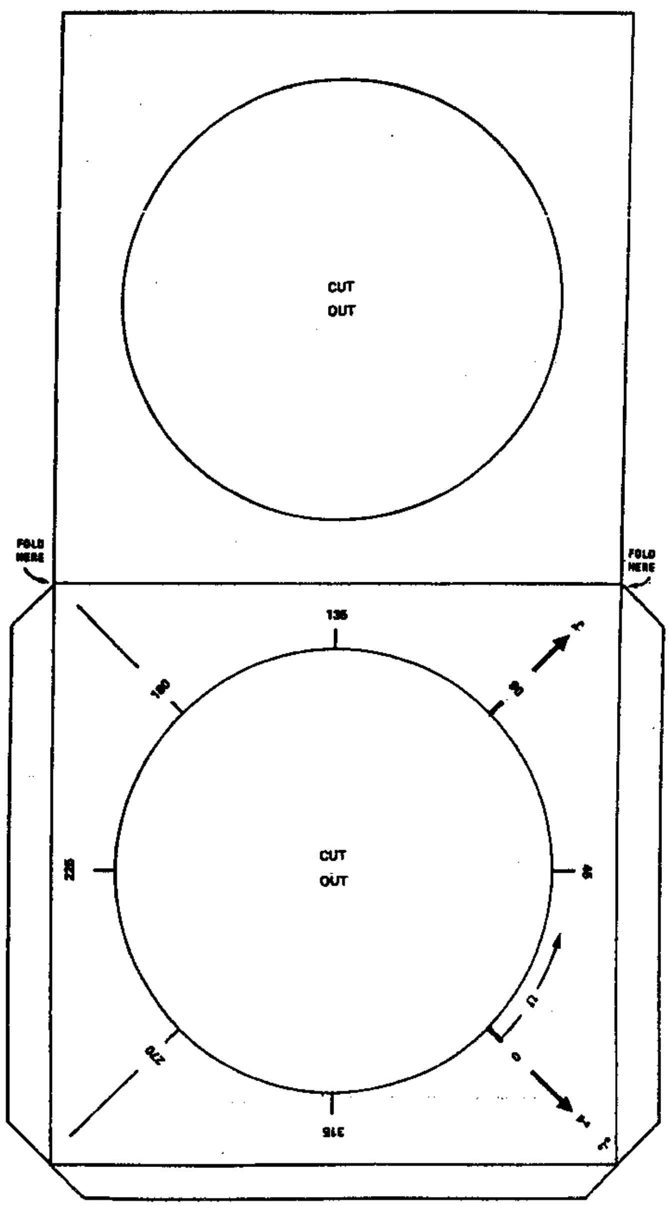
$$\omega = 90^\circ$$

$$\nu_0 = 270^\circ$$

(Answer: The satellite is at the ascending node. The $\bar{n}$ vector points away from the first point of Aries.)

Dec, 1986


A
B
C
D
LINE OF NODES
LINE OF NODES
180
135
90
45
0
315
270
225


CUT
OUT
FOLD
HERE
FOLD
HERE
135
225
CUT
OUT