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N91-22168

ADVANCED SPACECRAFT: WHAT WILL THEY LOOK LIKE AND WHY?

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ABSTRACT

The next century of spaceflight will witness an expansion in the physical scale of spacecraft, from the extreme of the microspacecraft to the very large megaspacecraft. This will respectively spawn advances in highly integrated and miniaturized components, and also advances in lightweight structures, space fabrication, and exotic control systems. Challenges are also presented by the advent of advanced propulsion systems, many of which require controlling and directing hot plasma, dissipating large amounts of waste heat, and handling very high radiation sources. Vehicle configuration studies for a number of these types of advanced spacecraft have been performed at the Jet Propulsion Laboratory over the past decade, and some of them are presented in this paper along with the rationale for their physical layouts.

SPACECRAFT CONFIGURATION

Over the years, the Jet Propulsion Laboratory (JPL) has studied many concepts for advanced and exotic spacecraft which might come to fruition in the 21st century. For a number of these studies, the author was involved in developing spacecraft mechanical configurations to integrate the various elements of a vehicle into an optimized structural and mechanical layout.

Advanced spacecraft concepts generally push the state of the art in propulsion, temperature control, materials, precision pointing control, size, mass, or packaging density. These requirements often conflict with one another, and complex trade studies must be undertaken to achieve an optimal design.

Integration of function, though often costly, is one method to reduce the size or mass of a vehicle. For example, using a pressure vessel or a thermal radiator as primary support structure, or integrating an antenna reflector and a solar power concentrator into a single structural component reduces the number of elements to be supported. The price to be paid is loss of modularity and more complex analyses and interfaces.

Requirements on fields of views for solar panels or radiators, or geometric constraints for radiation protection often force the layout of a vehicle to a particular configuration. Additionally, large vehicles in planetary orbits must trade off the above constraints against such external forces as gravity gradient and atmospheric drag. To avoid control problems, vehicles which are spin stabilized (or which rotate to be nadir pointed in a low planetary orbit) should be designed to rotate about one of the three principle inertial axes of the spacecraft, preferably about the axis of greatest inertia. This is especially important for large flexible structures.

In the end, trading off these many complex constraints requires an iterative approach which is often unique for each vehicle. Some attempts have been made to integrate the optimization of different disciplines, such as a combined structures and controls optimization, and in the future the spacecraft design process may become more direct and less iterative.

ADVANCED PROPULSION

Most space vehicles today utilize chemical propulsion with specific impulses of under 450 sec (or exhaust velocity less than 4.5 km/sec). Many advanced spacecraft of the next century will require more exotic forms of propulsion to achieve higher velocities or to carry greater payloads.

SOLAR SAILS

Solar sails are attractive because they utilize solar photon pressure for propulsion and therefore require no propellant. Large flat sheets of shiny material reflect sunlight, and some momentum is transferred to the reflective film. The resultant force depends upon the angle of incidence of the light, therefore the vehicle can be steered to direct the force vector in a desired direction.

JPL performed extensive studies of a Halley's Comet rendezvous mission in 1977, including a design for a three-axis stabilized square sail vehicle and a spin-stabilized "heliogyro" solar sail (reference 1). More recently, JPL has provided some support to the World Space Foundation in developing a smaller engineering test vehicle to demonstrate deployment and control of a solar sail and to obtain flight data (reference 2).

Spin-stabilized sails may provide higher performance because they require less support structure, but they are more difficult to steer rapidly because of the gyroscopic forces which must be overcome, and the attendant structural control problems inherent in a rapid precession maneuver for a large flexible vehicle. This is not much of an issue for vehicles in a solar orbit since the required turn rates are so slow. However, in a planetary orbit, a solar sail must typically turn at least 180° each orbit, which can lead to relatively fast turn rates for such a large flexible structure.

The World Space Foundation design (see Figure 1) calls for a 3,000 m^2 square sail which is supported by four simple cantilevered beams (spars) emanating from a central body. Three-axis attitude control is provided by steerable triangular vanes at the tips of the spars, and by moving a mass on a steerable boom to shift the center of mass relative to the center of solar pressure. The deployment sequence for the vehicle is rather simple as solar sails go (see Figures 2 and 3).

Square sails larger than about 5,000 m^2 probably cannot be supported by simple cantilevered spars and will require extensive stays and guy wires to stabilize the structure, as was the case with the Halley square sail. Autonomous deployment for that type of complex structure may be risky, and on-orbit construction may be preferred for such a vehicle.

Some disadvantages of solar sails are their low acceleration, typically about 1 mm/sec^2 at 1 AU, and their very low performance beyond the orbit of Mars. Their application of greatest utility may be as reusable interplanetary cargo shuttles for the inner solar system. High performance solar sails may find utility in Earth orbit for positioning communication satellites in non-equatorial locations using levitated geostationary orbits, or as non-orbiting hovering statites at high latitudes (reference 3). These two latter groups of vehicles do not require fast turn rates.

Related vehicles which could become prevalent in the coming millennium include the solar photon thruster (reference 4), laser sailing (reference 5), and microwave sailing (reference 5).

ELECTRIC PROPULSION

Electric propulsion (ion drive, arc jet, or plasma jet) will almost certainly be utilized in the next century due to its high performance (2,000 to 30,000 sec I_{sp}). One of the disadvantages of electric propulsion is the requirement for a high energy source (many kilowatts electric). This will most likely

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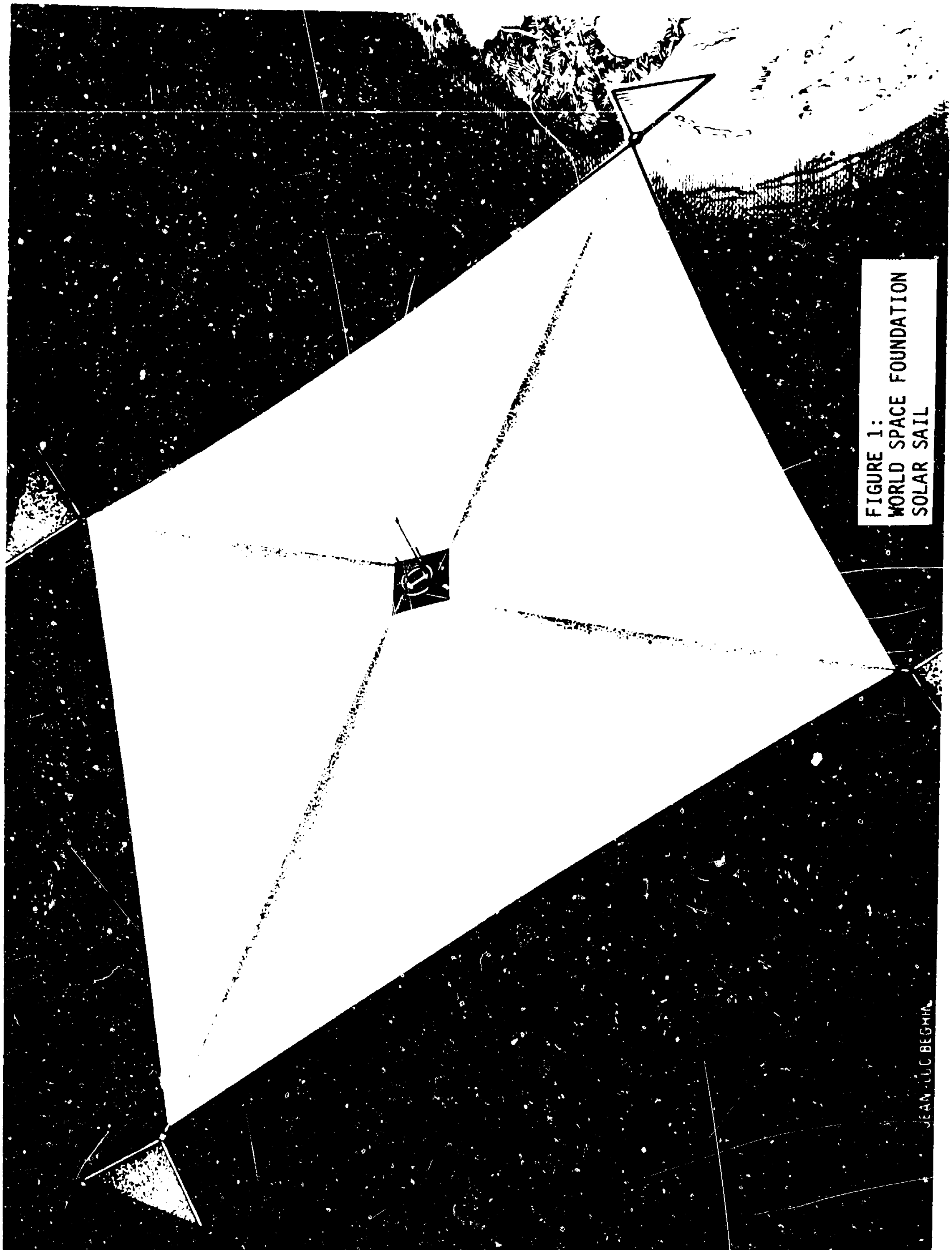


FIGURE 1:
WORLD SPACE FOUNDATION
SOLAR SAIL

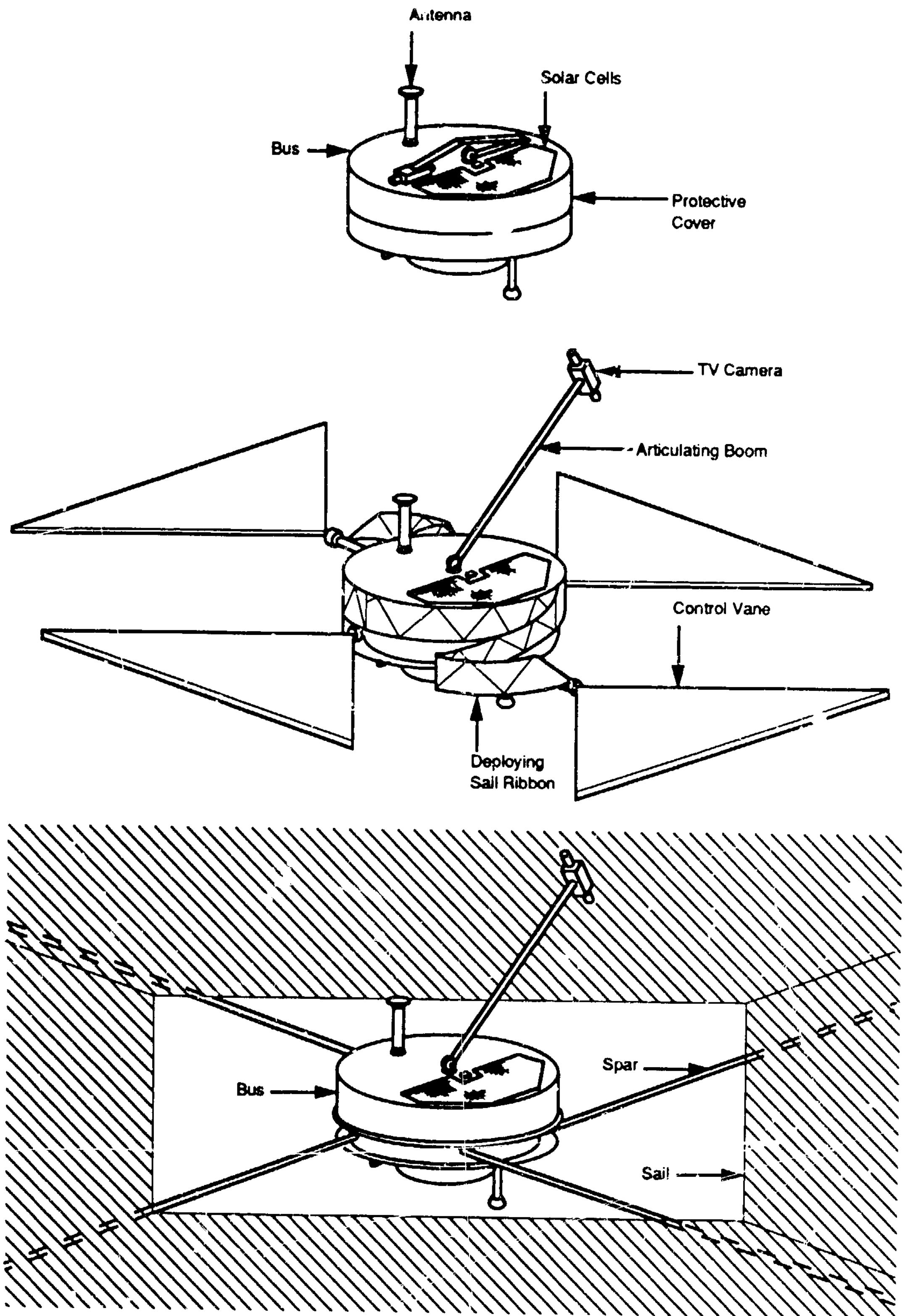


Figure 2: Deployment of Vanes and Spars on the
World Space Foundation Solar Sail Vehicle

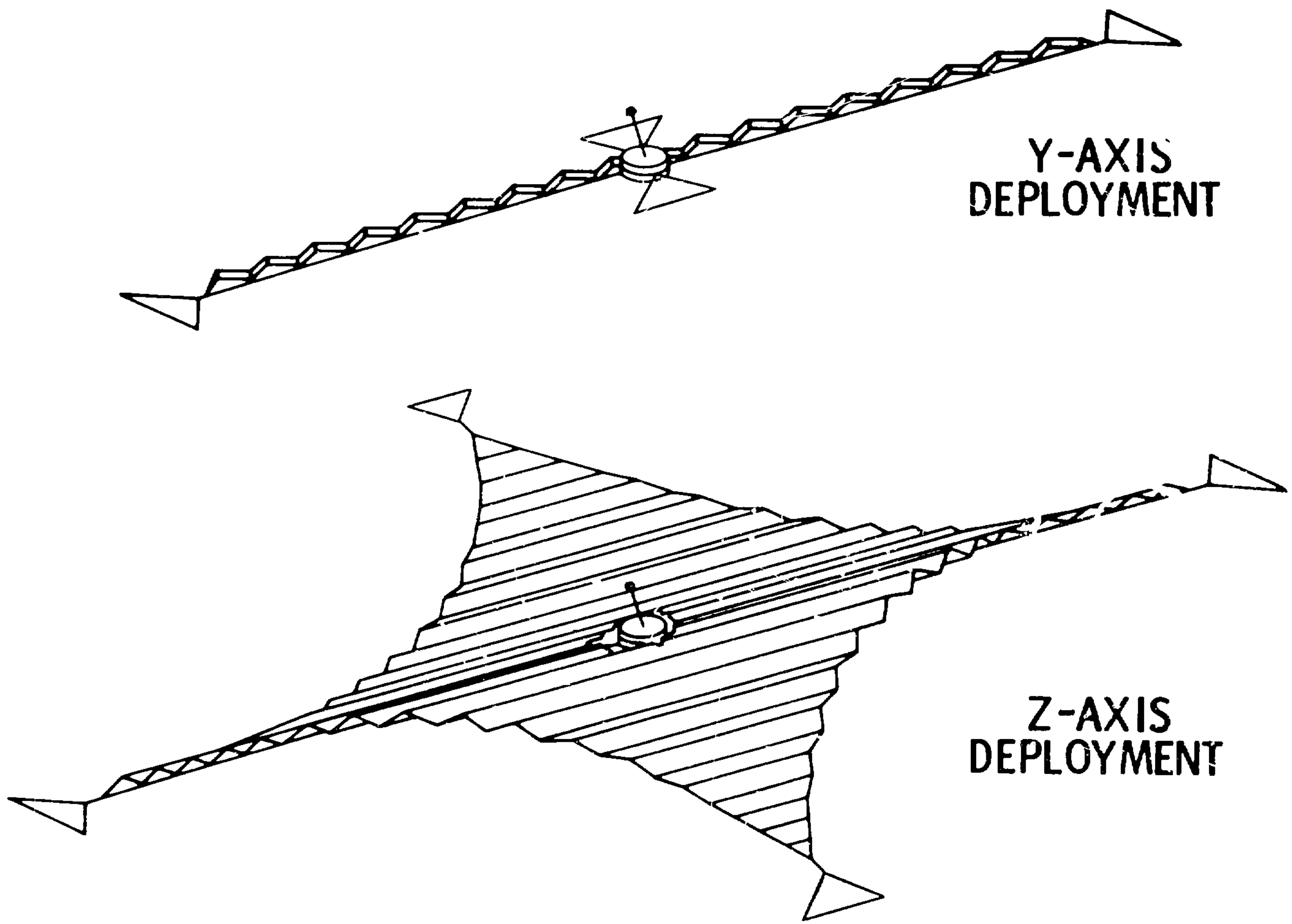


Figure 3: Deployment of Sail on the World Space Foundation Solar Sail Vehicle

be achieved by solar or nuclear means.

Power processing components for the ion thrusters require the dissipation of large amounts of heat. Additional heat rejection requirements arise from the solar or nuclear electrical generation system; therefore, these spacecraft will have significant radiator surfaces whose orientation must be maintained relative to the sun and also configured to minimize their field of view o the spacecraft itself. Clever vehicle design may tap some of this waste heat for useful purposes such as temperature control or secondary power generation. Ion drive has been extensively ground tested, space tested, and is in a state of immediate technological readiness.

Solar Electric Propulsion (SEP)

The development of multi-kilowatt solar arrays (SAFE, space station, APSA) brings SEP within easy technological reach, with all major components of the system having been developed. JPL has developed many designs for SEP vehicles including the detailed Halley flyby/Tempel 2 rendezvous mission studies in 1979-1980 (reference 6). A more recent SEP study was performed for the Mariner Mark II Project in 1986.

The Mariner Mark II (MMII) spacecraft is JPL's next generation of interplanetary spacecraft, now under development. The first two units, Comet Rendezvous/Asteroid Flyby (CRAF) and Cassini, will go to a comet and Saturn respectively. Follow on missions for the MMII vehicle class are planned. The addition of SEP would greatly enhance the utility of this spacecraft by expanding its propulsive capability.

The design depicted in Figure 4 integrates SEP as an add-on stage to what would be an already existing chemical propulsion system, except for the large solar arrays which are added to the main vehicle structure. The ion drive power processing electronics are integrated into a moderate sized radiator on the SEP stage. This design utilizes five independently gimbaled ion thrusters, and xenon propellant.

SEP places some additional configuration constraints over a standard propulsion system. Since the "burns" take place over several months rather than several minutes, the vehicle must be continually oriented to the thrust direction rather than to the sun during interplanetary cruise. This means the spacecraft must be able to tolerate sun illumination from a variety of directions. In addition, large steerable solar arrays must be continuously pointed at the sun, and sun must be kept off of the power processor radiator(s).

The MMII SEP design requires that the spacecraft maintain roll control about the thrust (Z) axis to keep the sun in the Y-Z plane (see Figure 4). The solar arrays are then articulated about the X axis to sun point, and the radiator is fixed in the Y-Z plane to avoid sun incidence. Roll control about the Z axis can restrict the sun to be in the -Y hemisphere, and a large sun shade is required to be added to the -Y side of the vehicle to protect it from broadside sun onto the chemical propulsion system and the electronics bays.

These additional complications to the spacecraft are somewhat costly, including provision for the launch stowage and later deployment of the large solar arrays, and the obscuration of science instrument fields of view by the large arrays. The large arrays also present some attitude control complications for the vehicle, but the enormous increase in propulsion performance makes SEP an enabling technology for many possible MMII missions.

Nuclear Electric Propulsion (NEP)

For missions which require propulsion beyond the orbit of Mars, NEP is generally favored over SEP. Using a nuclear fission reactor as its electrical source, NEP offers the benefit of much higher power and

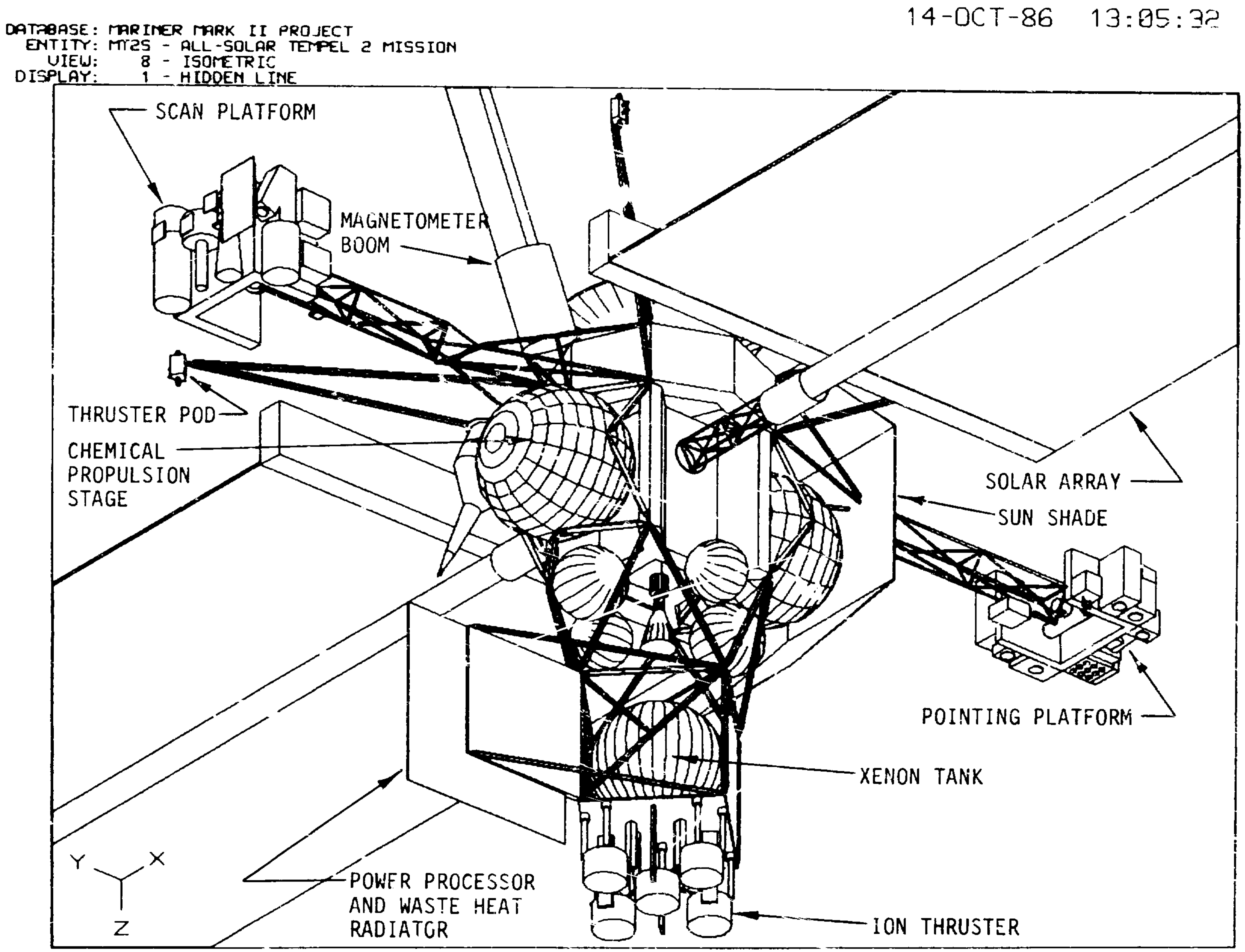


Figure 4: Mariner Mark II Spacecraft with Solar Electric Propulsion Stage

performance than SEP, independent of distance from the sun, with the disadvantage that extensive shielding and physical separation measures are required to protect most components of the vehicle from radiation emitted by the nuclear power source. Some of the most recent NEP studies at JPL have been in support of the Thousand Astronomical Units (TAU) mission, led by Aden and Marjorie Meinel.

The TAU concept uses NEP to accelerate a large spacecraft complex over a period of 10 years to a velocity of over 100 km/sec, heading out of the solar system from its original assembly point in Earth orbit. After fifty years, the vehicle will reach a distance of 150 billion kilometers (1000 AU, or 0.016 light years). Among its compliment of science instruments would be a large telescope to function as a wide baseline astrometric platform relative to the Earth from which to provide greatly improved estimates of interstellar distances and the Hubble constant.

The TAU design depicted in Figure 5 uses a 100 kW_e nuclear power supply based on the SP-100 reactor system. It is located at one end of the 43 m long complex. Most spacecraft subsystems and the scientific payload are located at the opposite end of the complex to achieve maximum separation for radiation protection. In the middle of the complex, desirably near the center of mass, is the ion propulsion system. These three major elements are connected by a long structural trusswork which could be either deployable or assembled in Earth orbit. The separation of the elements is dictated primarily by radiation constraints, requiring a trade-off of shielding mass versus truss structure mass versus cost of radiation hardening of components.

The configuration looks like a long stick, and the thrust direction is perpendicular to the long axis of the vehicle. The peak acceleration is about .5 mm/sec^2, so the structural loading is very slight, and the mass of the truss is driven by control stiffness requirements rather than by loads.

Both the nuclear power module and the ion drive module have substantial radiative cooling requirements. The configuration shown here utilizes cylindrical radiators in which the sun is allowed to illuminate them from any direction. If required, it would be possible to substitute flat radiator elements which could be kept edge-on to the sun by controlling roll about the vehicle's thrust axis.

A more recent study defines an option for a larger vehicle which is 140 m long, uses a 500 kW_e reactor system, and carries a larger payload (reference 7).

PLASMA PROPULSION

Missions requiring velocity changes greater than about 100 km/sec must look for more exotic forms of propulsion than ion drive can offer. Much higher specific impulses might be achieved by using nuclear energy sources to create a high energy plasma which can be expanded and directed at very high velocities. Since the plasma temperatures are too high for any solid material to contain, the plasma must be directed by a powerful electromagnetic field. An exception is the Orion concept (reference 8) which uses a heavy ablative blast shield.

Plasma propelled vehicles require an enormous investment in radiation protection. Perhaps the most challenging problem is in the shielding of the magnetic drive coils which must be relatively close to the plasma in order to contain it or direct it. A particularly clever concept was developed by Rod Hyde at Lawrence Livermore National Laboratory (reference 9) which utilizes only a single torroidal drive coil (Figure 6). The idea is to minimize the interception fraction of the plasma radiation with the drive coils and thereby minimize the mass of shielding required.

Magnetic plasma nozzles with multiple drive coils may more efficiently direct the plasma exhaust, but each coil requires its own heavy radiation shield with its attendant cooling requirements. Additionally, the radiation shield for one coil produces secondary radiation for which additional shielding must be

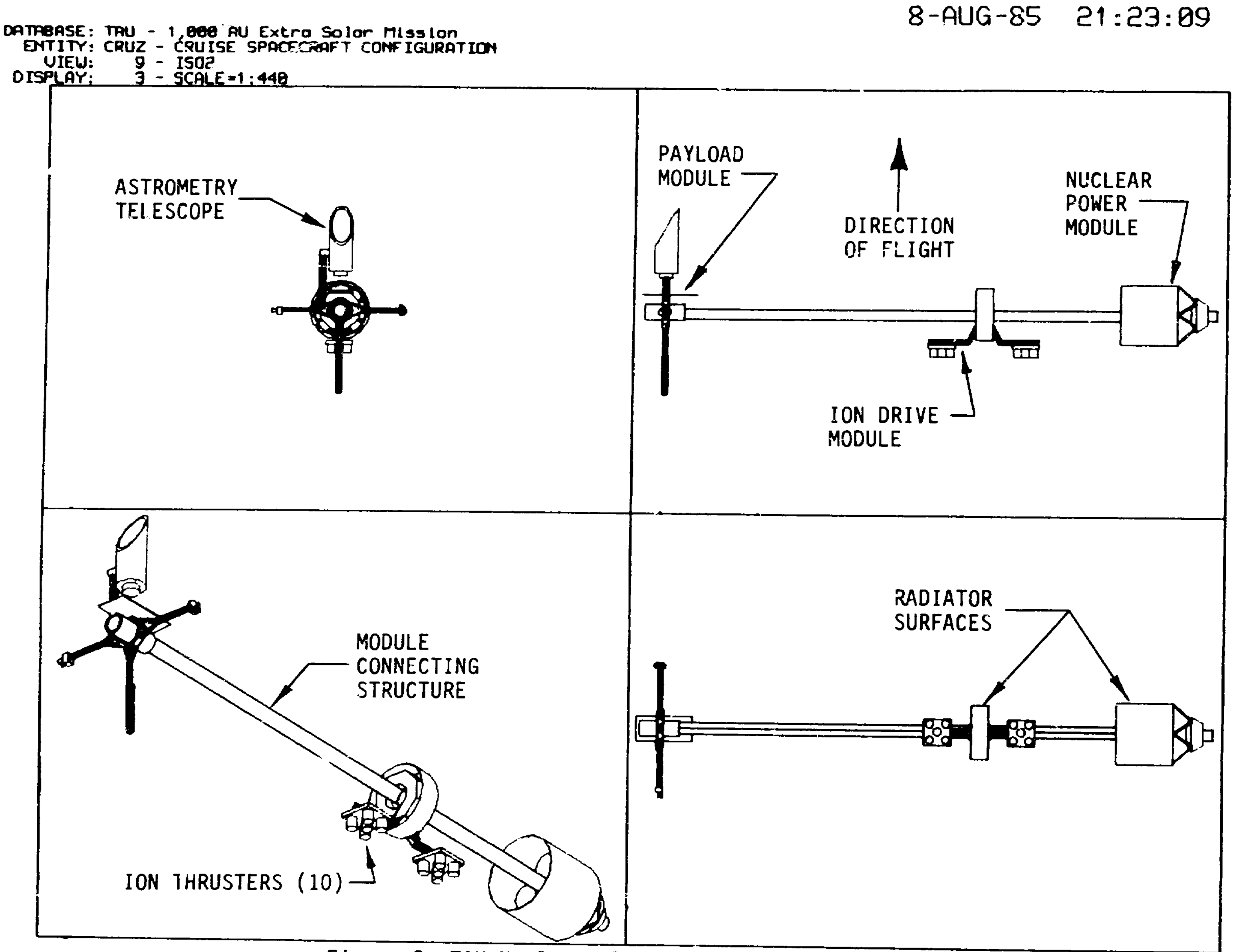


Figure 5: TAU Nuclear Electric Propulsion Vehicle

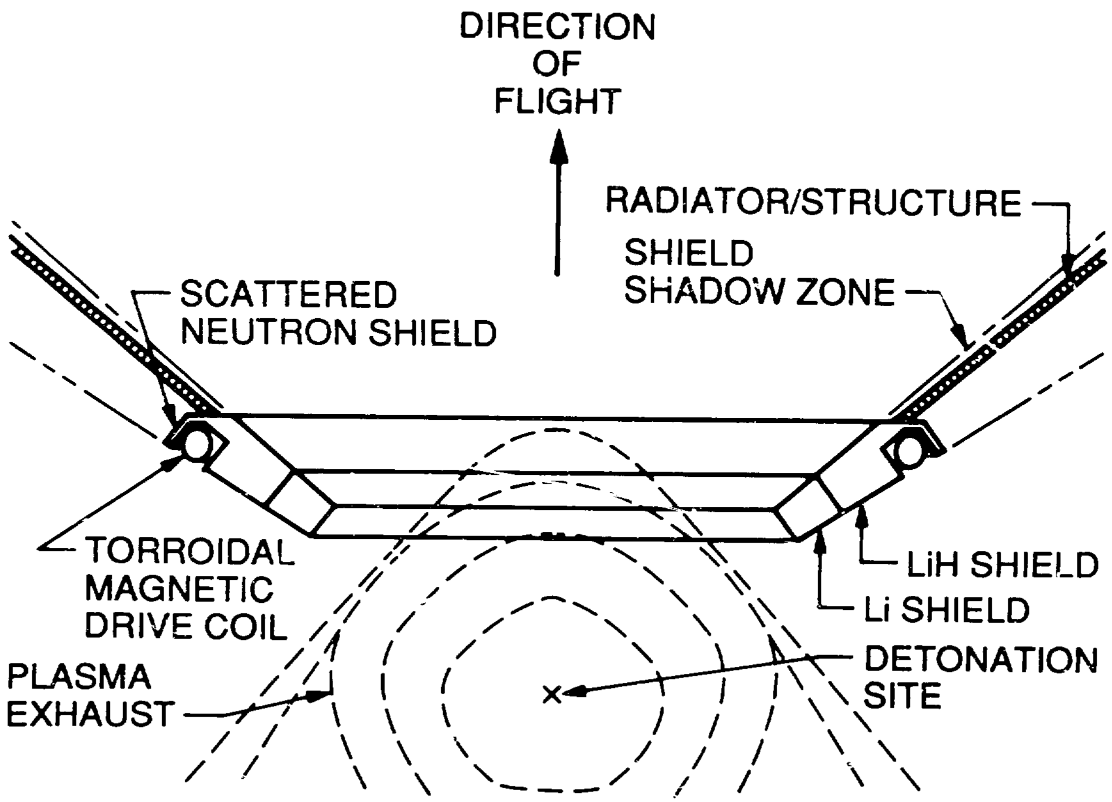


Figure 6: Geometry for Plasma Rocket Using a Single Magnetic Drive Coil

provided in adjacent coils.

The most prominent feature of any plasma propelled vehicle will be the waste heat rejection radiator surfaces, and a major portion of the waste heat will come from cooling radiation shields.

Adopting the Rod Hyde drive coil geometry, Joel Sercel of JPL first suggested trying to fit the entire vehicle into the shadow cone of the drive coil radiation shield, thus reducing shielding mass and cooling requirements to an absolute minimum. To integrate function, a conical shell radiator surface can also serve as the spacecraft's primary structure and provide the attachment base for all of the vehicle's various components. A torroidal propellant tank can be efficiently integrated atop the conical shell radiator (at the wide end of the cone), thus minimizing the field of view of the radiator to both the cryogenic propellant, cryogenic drive coil, and the hot plasma (see Figure 7). The structural load paths are direct and efficient.

The payload is supported atop the torroidal propellant tank, minimizing its exposure to radiation. Thus, the optimized vehicle is a large conical shell traveling with the wide open end forward, expelling plasma out the drive coil at the narrow aft end of the cone. For even more advanced propulsion options, such as the Bussard ramjet (reference 10), the cone might be adapted into a scoop to obtain additional reaction mass from the interstellar medium.

Fusion Propulsion

In 1986-1987, JPL participated in a study led by Charles Orth at Lawrence Livermore to develop a conceptual design for an Inertial Confinement Fusion (ICF) rocket named VISTA (Vehicle for Interplanetary Space Transport Applications, reference 11). The vehicle would use many high energy lasers mounted around the surface of the cone described above, and mirrors would direct the beams to a detonation site at the apex of the cone. Pellets of deuterium, tritium, and hydrogen expellant mass would be ejected on a trajectory to the detonation site, and once reaching the site, the bank of lasers would pulse fire at the pellet, imploding it to initiate a fusion reaction, creating a high energy plasma which would be directed by the drive coil's magnetic field.

Pellets would be ejected and imploded at a rate between 5 and 30 per second, resulting in a pulse-mode rather than a continuous propulsion system. It is estimated that such a system could achieve an acceleration of 0.02 g or greater, with a specific impulse of about 25,000 sec. Typical mission velocity changes are 100 km/sec or more.

The point design for the VISTA study was a manned Mars vehicle with a 45 day trip time to Mars for rendezvous (see Figure 7). The dry mass was 1,600,000 kg, excluding the payload of 250,000 kg which included crew accommodations, crew shielding, and lander craft. The propellant mass was 4,150,000 kg for a total loaded vehicle mass of 6,000,000 kg. Of this, the primary structure/radiator was estimated to be 200,000 kg.

A NASTRAN finite element structural analysis was performed by Rob Calvet at JPL for the primary structure. The shell structure was assumed to consist of titanium alloy heat pipes integrated together with local stiffeners and structural attachment points provided for mounting and thermally isolating various spacecraft components. It was determined that special shock mounting of the pulsed propulsion drive coil is not required. The mass of the drive coil itself and the compliance of the surrounding structure form a sufficient mass-spring momentum absorber to sharply attenuate the drive pulse peak loads. Several meters out along the shell, away from the drive coil, only an averaged acceleration is seen by the structure.

The mass area-density arrived at for the primary radiator/ structure was 14 kg/m^2. Stretching the current

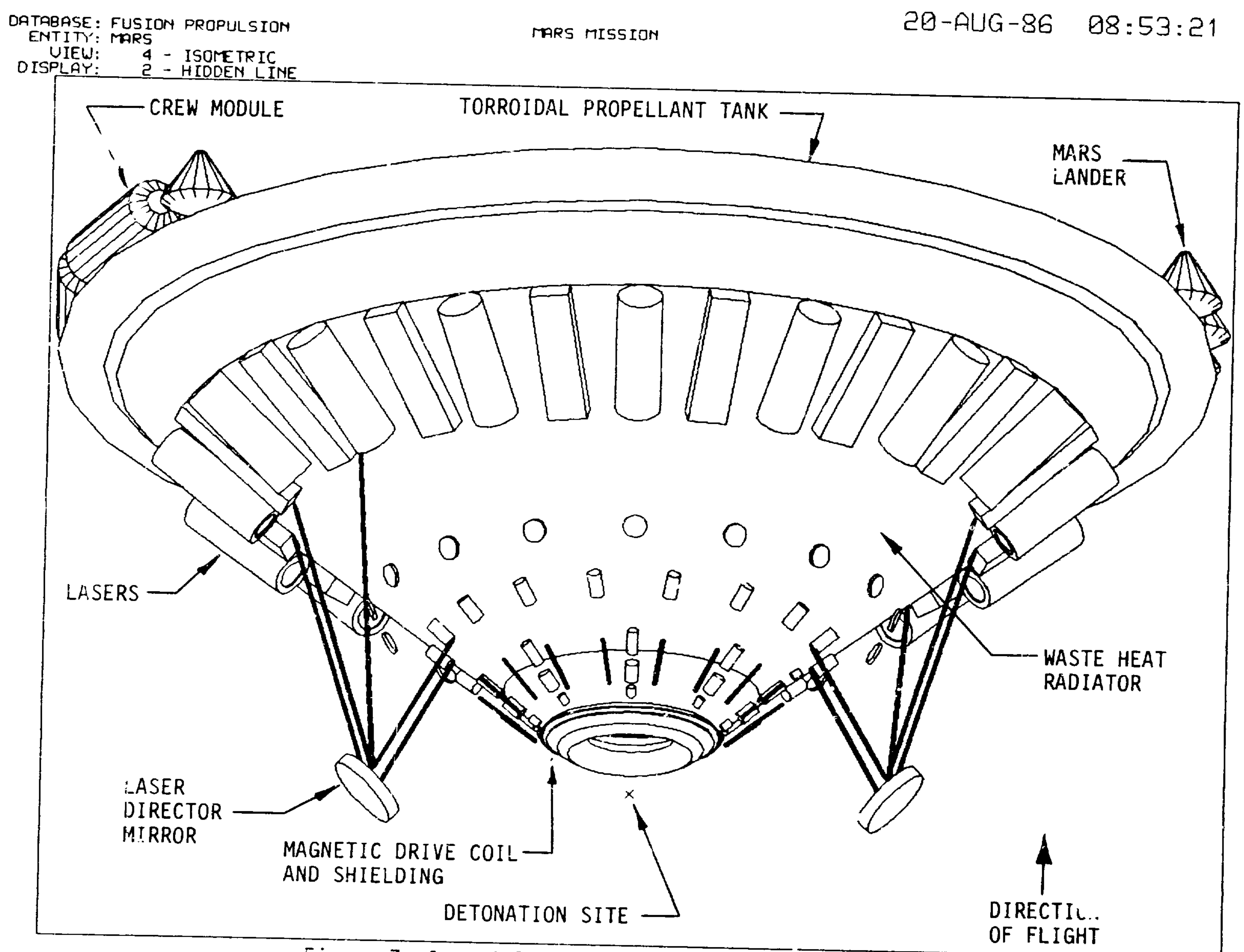


Figure 7: Inertial Confinement Fusion Rocket Vehicle

state of the art, radiators are envisioned with mass area-densities as low as 1.5 kg/m^2. Although idealized stresses in this thin of a structure are probably still acceptable, one must be concerned about stiffening for local buckling, structural stiffness (first mode frequency) for stability and control, meteoroid protection, and manufacturability, among other things. For mass estimation purposes for this type of vehicle configuration, one should probably use a value of 10 kg/m^2 for the primary radiator/ structure.

Antimatter Propulsion

Matter/antimatter annihilation may someday promise even higher performance vehicles than fusion propulsion. Rather than imploding D-T pellets to create a high energy plasma, protons and antiprotons would be placed in contact at the detonation site. Besides resulting in a more efficient conversion of matter into energy, the lasers and mirrors required for the VISTA concept would be eliminated (reference 12). Also the waste heat radiator requirements of the lasers are eliminated, although large radiator surfaces are still required for the magnetic drive coil shield. Cooling must also be provided for the energy system which powers the drive coil. This system could either extract energy from the plasma through induction, possibly using the existing drive coil, or use waste heat for a thermodynamic cycle engine.

John Callas at JPL has performed monte carlo particle interaction analyses for several configurations of antimatter rockets, one of which (the beam-core) is similar to the configuration described here (reference 13). The analysis considered numerous loss mechanisms, including gamma ray losses and magnetic "mirror" losses. His analysis is for a system with no additional expellant mass added to the annihilation reaction. This system is expected to result in a conversion efficiency of annihilation energy into useful propulsion of under 20%; however, the annihilation energy is of a considerable magnitude.

Figure 8 depicts an interstellar vehicle which might use matter/ antimatter annihilation propulsion. The vehicle is quite large (about 1 km diam.), as is indicated by the Space Shuttle shown for scale. This size is representative of a single stage vehicle which might travel to the star Epsilon Eridani (10.7 light years) and stop there within a time span of 100 years. By placing a second smaller torroidal propellant tank partway up the conical shell structure, it might be possible to stage (jettison) the upper radiator area and larger propellant tank at the top halfway through the mission, retaining the lower section (with its smaller tank), and thereby improve performance.

EXTENDED SCALE SPACECRAFT

In the 33 years of the Space Age, spacecraft have ranged in size from 1.5 kg and 0.16 m (Vanguard 1) to 100,000 kg and 37 m (Shuttle orbiter and payload). The next century will see the range in scale of spacecraft expanded in both extremes.

Micro Spacecraft

Advances in microelectronics, Very Large Scale Integration (VLSI), and microrobotics will allow for the reduction in size and mass of spacecraft to an unprecedented degree. This will be useful for achieving higher velocities and faster trip times, putting more spacecraft on existing launch vehicles, allowing for smaller launch vehicles, or utilizing electromagnetic launchers.

In the early days of the U.S. space program, there were a few spacecraft that would qualify as micro spacecraft, such as Vanguard 1 and Pioneer 3/4. The latter vehicle, using 1958 technology, weighed only 5.9 kg and was only 0.2 m in diameter and 0.4 m tall, yet had a respectable imaging camera (among other scientific instruments) and could transmit data to Earth from beyond Lunar distances. The current generation of "light-sats" include AMSAT's Microsat which is 0.23 m on a side and weighs 10 kg.

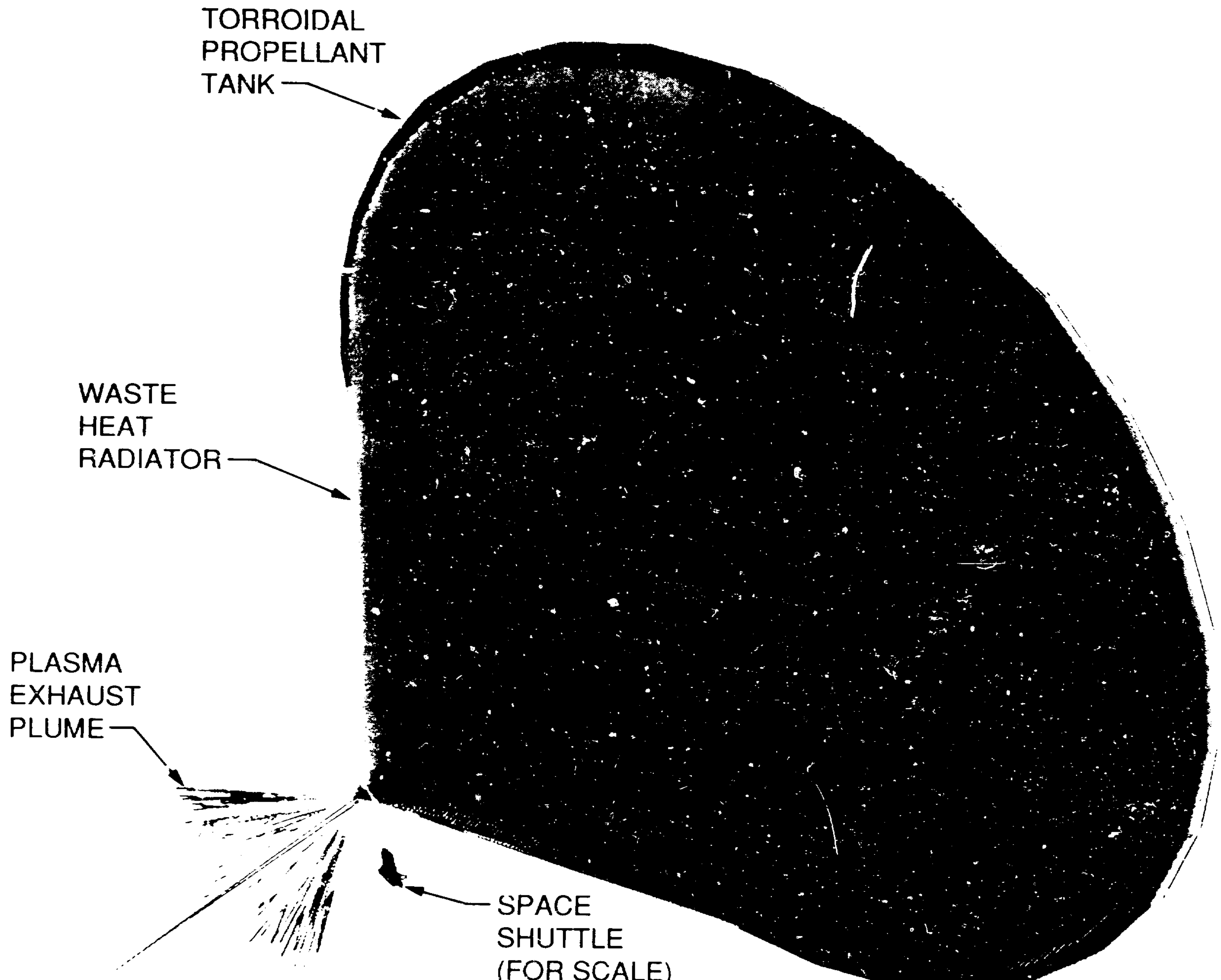


Figure 8: Interstellar Vehicle Utilizing Matter/Antimatter Propulsion

Microspacecraft development at JPL (since the days of Pioneer 4) includes studies performed by Jim Burke in 1980 (reference 14) and more recent work by Ross Jones (reference 15). One recent small spacecraft concept studied by Kerry Nock and Ron Salazar is the Lunar GAS (Get Away Special, reference 16) shown in Figure 9. This vehicle would be deployed from a Shuttle GAS canister and utilize SEP to reach lunar orbit, starting from low Earth orbit.

In its ultimate limit, one might envision the microspacecraft as a monolithic silicon block with integrated circuits, solar cells, phased array antenna, and other spacecraft subsystems integrated together into one "chip". Recent advances in the fields of microscopic motors and microrobotics may lead the way to subminiature planetary rovers.

Mega Spacecraft

In the coming millennium, requirements will continue to grow for larger spacecraft such as space station complexes, tethered satellite platforms, space-based radar, large precision interferometers and segmented reflectors, solar power stations, solar sails, etc. Challenges will be presented in making these structures as light weight as possible, and in controlling their geometry, orientation, and pointing stability. Some of these platforms and vehicles will utilize fixed structures and passive damping, while others will require active structural elements and special control actuators dispersed throughout the structure to control its stability and/or allow it to achieve precision pointing control.

JPL is one of several NASA centers involved in a Control Structure Interaction (CSI) program to study and develop control techniques for such large structures. A major focus of JPL's work is a conceptual design for a large space-based interferometer to be used for high resolution imaging and precise astrometry (reference 17). This structure uses piezo-electric devices to control strut length and dynamic characteristics, proof mass actuators to control damping (in addition to passive damping elements), and voice coils and piezoelectric stacks to position optical elements.

As shown in Figure 10, the Focus Mission Interferometer (FMI) consists of a long box truss which supports three separate interferometer telescope systems for which positioning must be controlled to tolerances as small as a few nanometers. A separate metrology tower contains ranging and position measuring optical systems which provide feedback to the active control system. Although the FMI is only 26 m in length, the technology embodied in it can enable much larger actively controlled space structures to be built.

Large space complexes can also be enabled with tethered systems stabilized by gravity gradient, centrifugal, or other forces. One recent JPL study led by Dave Collins involves a Martian aeronomy subsatellite which would be deployed from and tethered to a Mars orbiter spacecraft, similar to the Shuttle tethered satellite system. Figure 11 depicts a small U.S. vehicle deployed from a Soviet orbiter in a cooperative effort.

OTHER ADVANCED CONCEPTS

There are of course many other concepts for vehicles of the next millennium than those few presented here. Of immediate utility are aerocapture and aerobraking which use atmospheric drag to reduce propulsion requirements for orbit insertion and orbit lowering maneuvers. The savings in propellant mass are traded off against the mass of the aeroshield and the configuration and mass penalties resulting from having to fit within the aeroshield and meet its center of mass requirements.

The NERVA (Nuclear Engine for Rocket Vehicle Application) rocket engine stands at a high level of readiness for usage in interplanetary travel requiring large payloads or high velocities. Beamed propulsion concepts using lasers, microwaves, etc. may well find utility in the next century, as may space

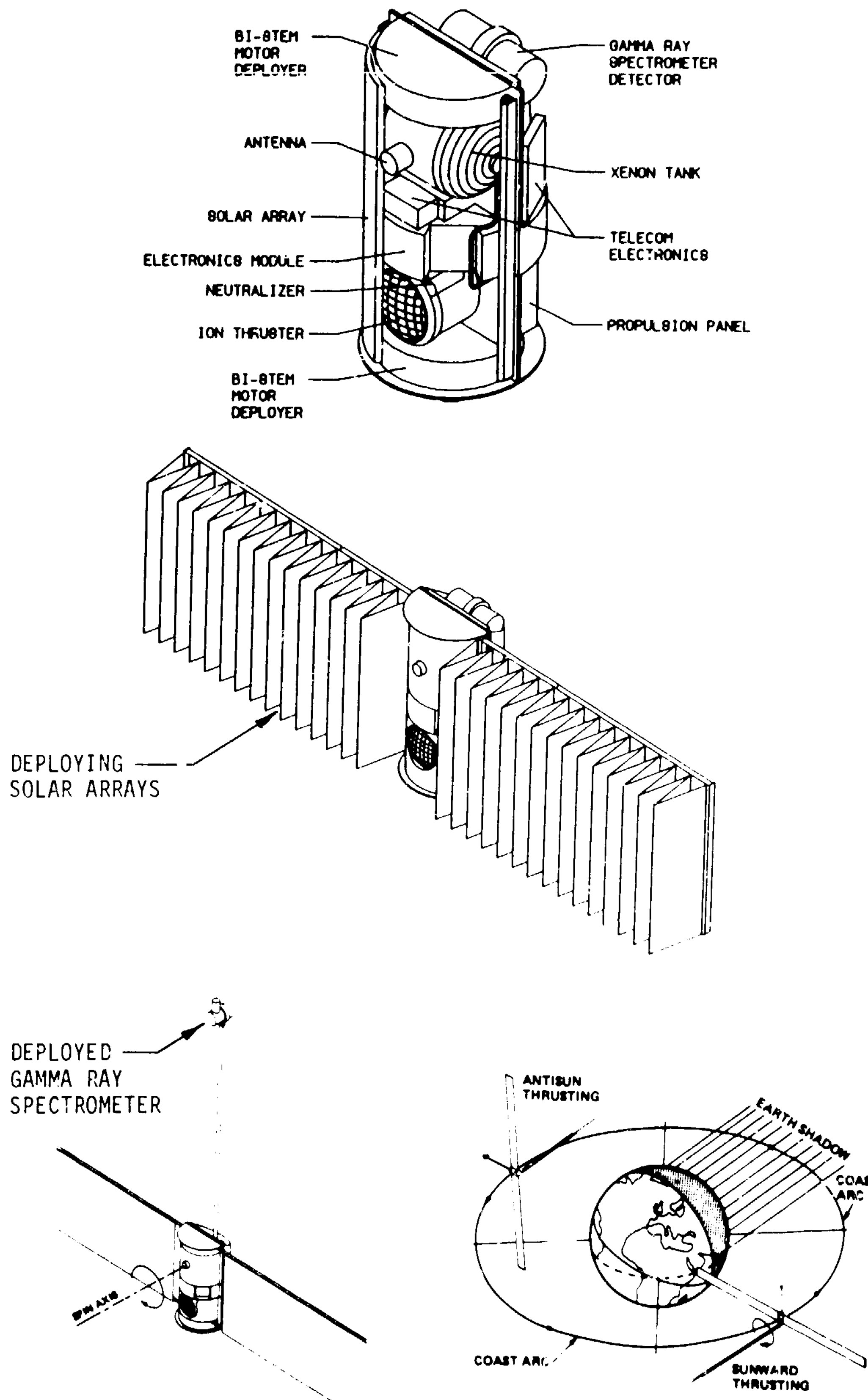


Figure 9: Lunar "Get Away Special" Spacecraft

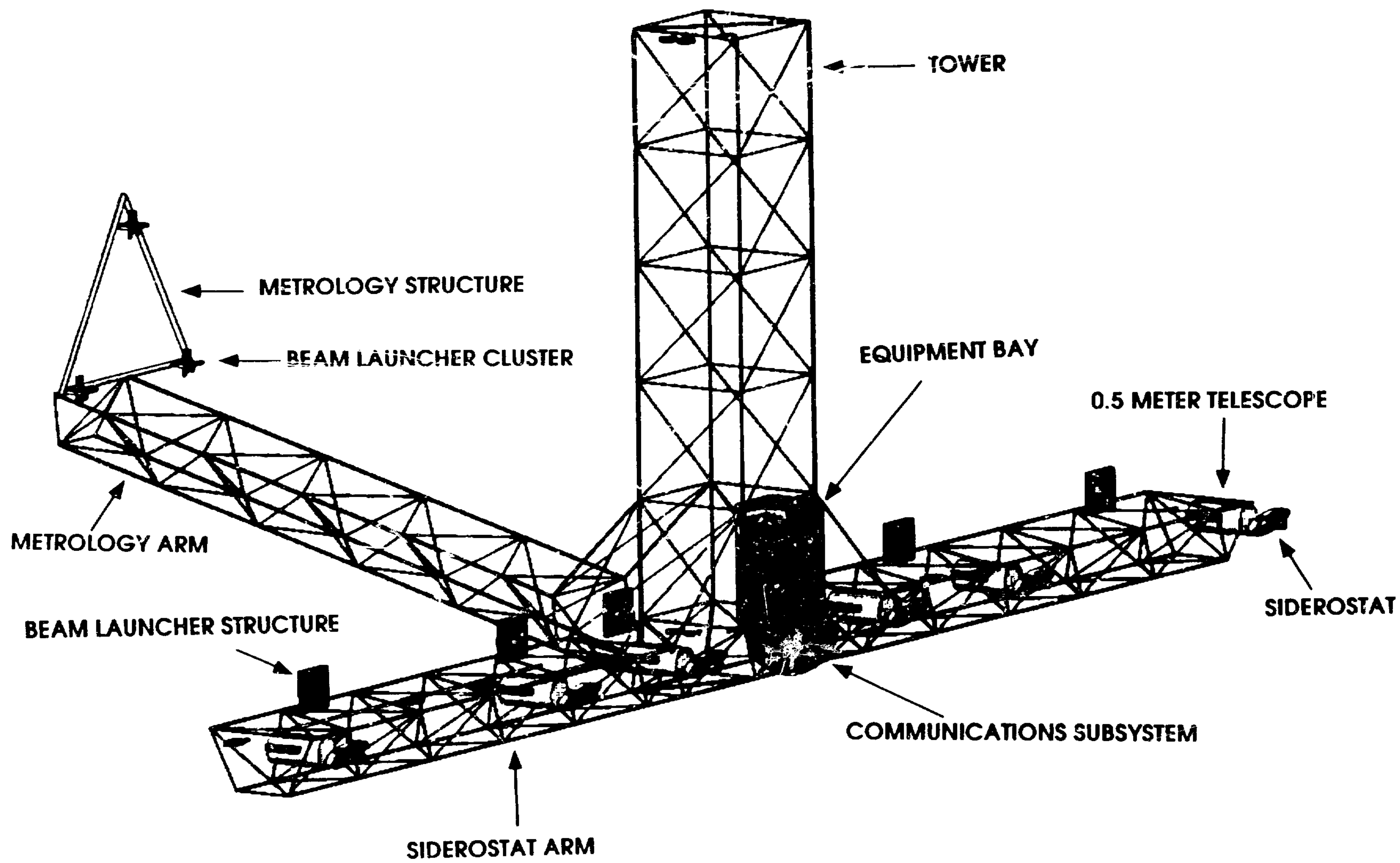
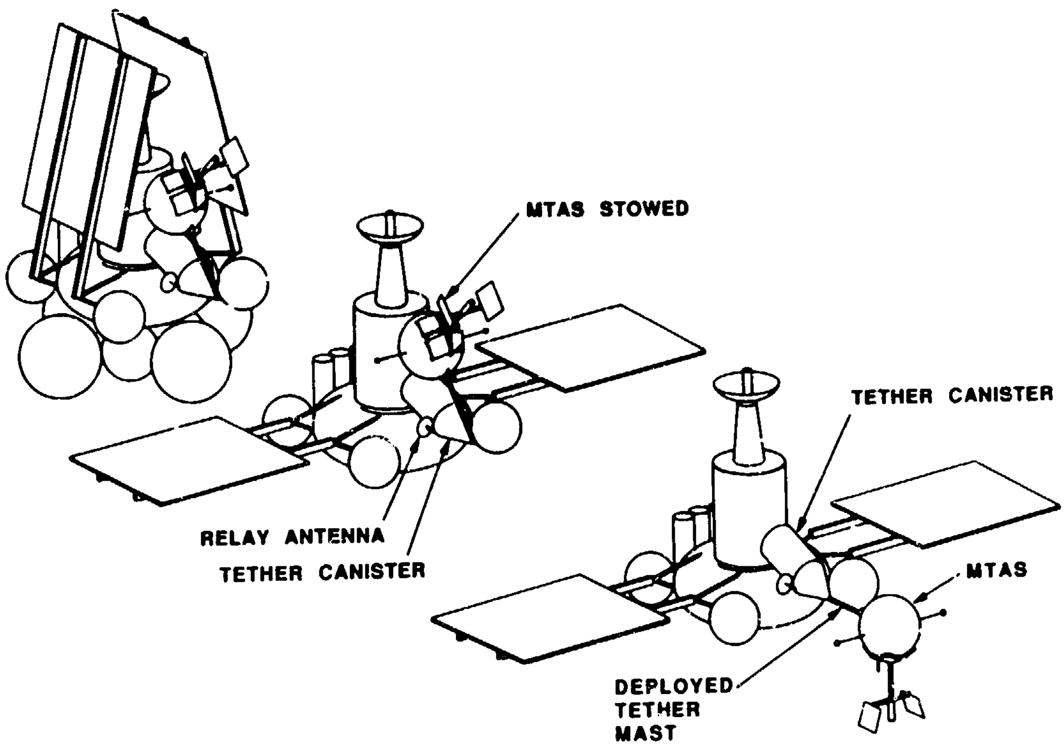


FIGURE 10: THE FOCUS MISSION INTERFEROMETER

MARS TETHERED AERONOMY SATELLITE STUDY

MTAS/MOTHER SPACECRAFT

LAUNCH, CRUISE, AND PRE-RELEASE CONFIGURATION



MTAS/MOTHER SPACECRAFT CONFIGURATION DURING MTAS MISSION

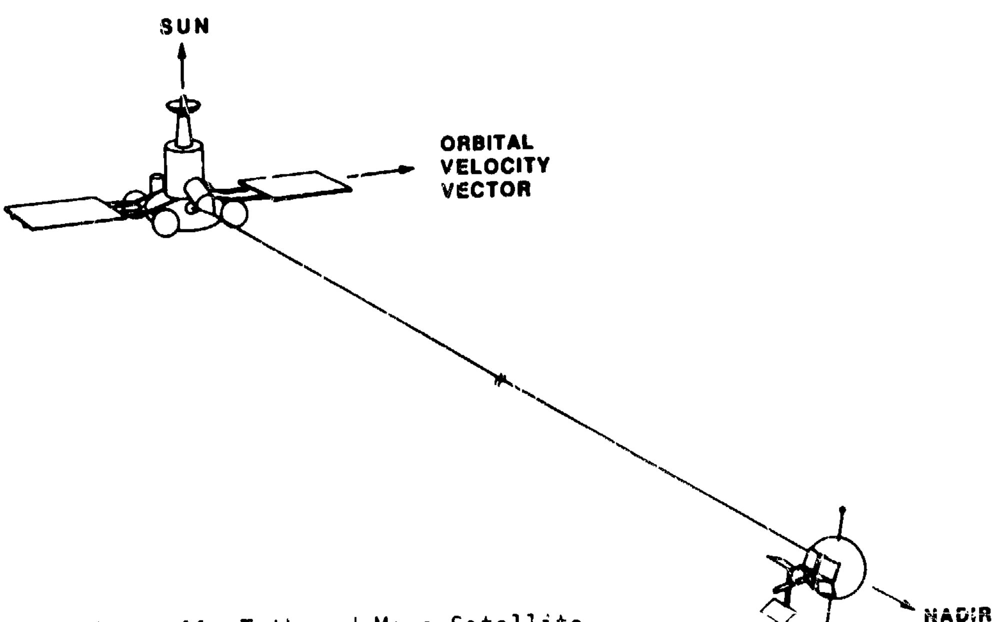


Figure 11: Tethered Mars Satellite

or Earth based electromagnetic launchers. For achieving interstellar travel velocities, the Orion concept is probably a nearer term solution than either fusion or antimatter propulsion.

What will the advanced spacecraft of the next millennium look like? We can only make engineering judgments based on our imagination, our current understanding of physics, and extrapolations of technologies we are aware of today. On one hand we always fail to realistically estimate the performance losses and difficulties inherent in bringing abstract physical principles to practical engineering realization. On the other hand we always fail to imagine the unexpected physical discoveries and new technologies that the future will bring.

ACKNOWLEDGMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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