ALFA: A Constellation Mission for Low Frequency Radioastronomy[1]

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Abstract - The ALFA mission is proposed to be the first astronomical observatory to make high-resolution radio images in the vast region of the electromagnetic spectrum below Earth's ionospheric cutoff between 30 kHz and 30 MHz. The ALFA imaging interferometer consists of 16 identical small satellites with dipole antennas and low frequency radio receivers, distributed in a spherical array 100 km in diameter, yielding images with thousands of times the resolution previously available in this frequency range. The array will be placed in a nearly circular distant retrograde orbit about the Earth, with a typical range of 10^6 km. Each satellite communicates directly with a small (11 m.), low-cost antenna at each DSN site, providing parallel data paths and continuous coverage. As a result, the array is resilient to individual satellite failures; observing by the rest of the array will be unaffected.

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1. INTRODUCTION

The Astronomical Low Frequency Array (ALFA) mission was proposed to NASA's Medium-class Explorer Program to produce the first low frequency, high resolution radio images of the solar corona and interplanetary disturbances such as shocks driven by coronal mass ejections (CMEs). For the first time scientists would be able to image and track these solar disturbances from the vicinity of the sun all the way to 1 AU. This requires observing frequencies from tens of MHz to tens of kHz, and since Earth's ionosphere severely limits radio interferometry from the ground at frequencies below ~30 MHz, these measurements must be made from space. ALFA, which is a radio imaging interferometer, will operate from 0.03 to 30.0 MHz.

One of the major space weather goals of the ALFA mission is accurate prediction, days in advance, of the arrival of CMEs at Earth. CMEs interacting with Earth's magnetosphere can result in geomagnetic storms which are capable of damaging satellite and electric utility systems and disrupting communications and navigation services. Solar disturbances can also pose a threat to astronauts. For this reason, successors to ALFA may become as indispensable for future space weather forecasting as weather satellites are today. ALFA was designed to be launched shortly after solar maximum when some of the most energetic solar disturbances are expected. In addition, ALFA can image Earth's magnetospheric response to such solar disturbances, providing a unique global view of the magnetosphere from the outside.

The ALFA mission can also produce sensitive, high resolution radio images of the entire sky at frequencies below 30 MHz, a region of the spectrum that remains unexplored with high angular resolution. Many physical processes involved in the emission and absorption of radiation are only observable at low radio frequencies. For example, the coherent emission associated with electron cyclotron masers, as seen from the giant planets, Earth, and several nearby stars, is not only expected to occur and be detectable elsewhere in the galaxy but to be ubiquitous. Incoherent synchrotron radiation from fossil radio galaxies can be detected by ALFA, revealing the frequency and duration of past epochs of galactic nuclear activity. It is also likely that unexpected objects and processes can be discovered by ALFA. Indeed, one of the exciting aspects of the mission is its very high potential for new discoveries.

ALFA's science goals are linked to specific topics in NASA's Sun-Earth Connection (SEC) and Structure and Evolution of the Universe (SEU) themes. In the SEC area, the mission science goals address:

- solar variability --- physics of solar transient disturbances, the evolution of coronal and solar wind structures, and interactions of plasma and magnetic field topology.
- terrestrial response --- solar interactions with Earth's magnetosphere, geomagnetic storms, and space weather.
- implications for humanity --- forecast the arrival of coronal mass ejections.

In the SEU theme area, ALFA will address:

- galaxy evolution --- detection of fossil radio galaxies and very-high-redshift radio galaxies, and cosmic ray diffusion times and magnetic field distributions in galaxies.
- life cycles of matter --- distribution of diffuse ionized hydrogen in the interstellar medium, energy transport via interstellar plasma turbulence, origin of cosmic ray electrons, and the detection of old galactic supernova and gamma-ray burst remnants.
- discover new phenomena and test physical theories --- new sources of coherent radio emission, pulsar emission regions, shock acceleration, physics of electrically charged dusty plasmas, and new classes of objects not seen at higher frequencies.

History and Basis

The fundamental technique of ALFA is aperture synthesis, in which interferometric data from a large number of baseline lengths and orientations are combined to produce images with an angular resolution comparable to that of a single aperture the size of the entire interferometer array. This is the basis of ground-based arrays such as the VLA and VLBA and the VSOP space VLBI (Very Long Baseline Interferometry) mission, and results in many orders of magnitude improvement in angular resolution. The concept was endorsed by the radio astronomy panel of the Bahcall (1991) decade review committee[1], which recommended "...establishing a program of space radio astrophysics during the next decade leading to the establishment of a Low Frequency Space Array, a free flying hectometer wavelength synthesis array for high resolution imaging, operating below the ionospheric cutoff frequency." The technology now exists to carry out this mission inexpensively.

The ALFA imaging interferometer consists of 16 identical small satellites with dipole antennas and low frequency radio receivers, distributed in a spherical array ~100 km in diameter. The array will be placed in a nearly circular retrograde orbit ~10^6 km from Earth. The size of the ALFA array is determined by a fundamental limit to angular resolution created by the scattering of radio waves in the interstellar and interplanetary media. However, this scattering limit is a strong function of direction and observing frequency. To allow for this, it will be possible to vary the size of the array during the mission to increase or decrease the maximum angular resolution.

Figure 1 shows the angular resolution of ALFA compared to several ground-based radio arrays and to the angular broadening caused by interstellar scattering at intermediate galactic latitudes. The shade region is inaccessible from the ground with useful angular resolution. Figure 2 and Table 1 indicate how the number of satellites, array orbit, and antenna and receiver design values are derived.

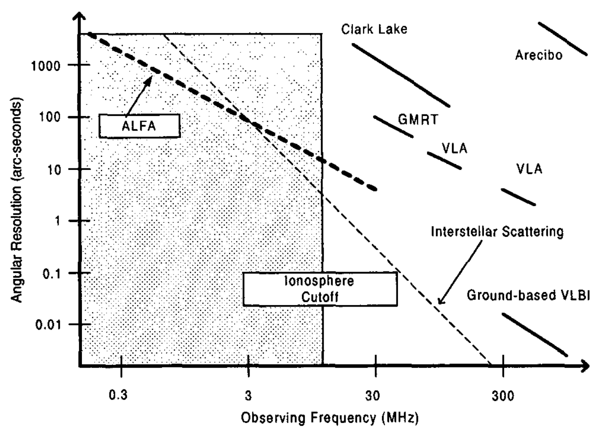

Figure 1 Angular resolution of the ALFA array as a function of observing frequency

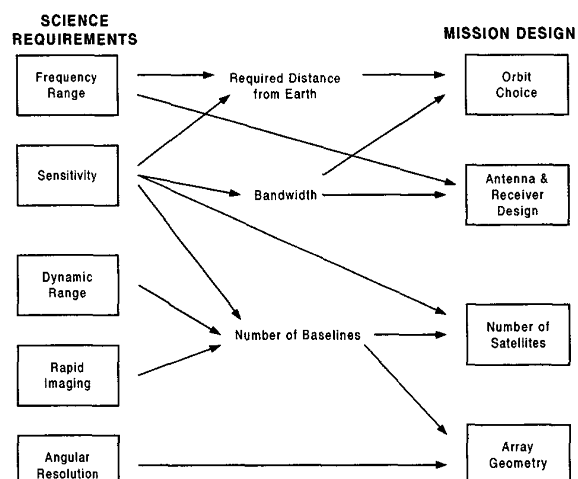

Figure 2 The ALFA mission criteria for selection are derived from observational capabilities needed to meet the science objectives

Table 1. Detailed observing requirements

Science Requirement	Mission Parameter
Observe below Earth's ionosphere cutoff freq.	Freq. range: 30 MHz to 30 kHz (local plasma freq.)
Angular resolution of ~1 arcminute at 10 MHz	~100 km maximum array baseline length
Good instantaneous aperture plane sampling	120 simultaneous baselines (16 array satellites)
Sensitivity at 10 MHz of 50 Jy in less than 1 hour	Up to 125 kHz bandwidth, 16 pairs of dipole antennas
Dynamic range ~1000 for fields far from the sun	3-D array geometry, dense aperture plane sampling

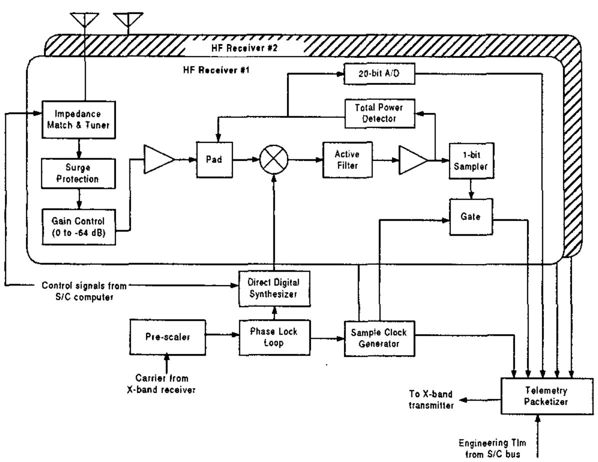

Figure 3 Low frequency receiver block diagram

2. INSTRUMENTATION

The science instrument for ALFA is the entire array of sixteen satellites operating together as an interferometer. Low frequency radio radiation will be sampled by a pair of orthogonal dipole antennas on each of the identical satellites, and each dipole will feed signals to a simple but flexible high dynamic range receiver. The dipoles are 10 m long, determined by the availability of self deploying, flight-proven beryllium copper tape antenna elements. Observing frequency, bandwidth, sample rate, and phase switching of the receivers are controlled by the central spacecraft processor, and can be changed at will. A block diagram of the receiver is shown in Figure 3 and receiver performance characteristics are listed in Table 2.

Table 2. Performance characteristics

Frequency Range	0.03 - 30.0 MHz
Frequency Resolution	10 kHz steps
Bandwidth	Up to 125 kHz
Sample Rate	2 samples/cycle
Bits/Sample	1
Total Power Sampling	20-bit (60 dB) range, 5 sec. per sample
Dynamic Range	>90 dB

The receiver is a straightforward, single channel design based on commercially available components. It covers 30 kHz to 30.0 MHz, with Nyquist sampled bandwidths up to 125 kHz and an ability to handle a very wide range of input levels. The single bit sampling technique was chosen to reduce the required downlink bandwidth while minimizing the impact on the signal to noise ratio (about 2 dB).

The ALFA constellation will have a maximum baseline length of ~100 km, which provides a good overall match to interstellar and interplanetary angular broadening. The array is placed in a nearly circular retrograde orbit about the Earth-Moon barycenter, with a typical distance from Earth of one million km. There are many advantages to using this type of orbit for this mission, including sufficient distance from Earth to minimize terrestrial interference combined with the ability of each satellite to communicate directly with relatively small (11-meter) and affordable ground stations. Note that this approach involves no reliance on a single spacecraft for data relay or any other mission critical function; the array data path is extremely robust (16-way redundancy) all the way to the ground. Similarly robust is our technique for continuously monitoring the relative positions of the satellites by measuring the separations between all pairs of satellites. This provides far more constraints than are needed to solve for all of the relative positions. Should one or more of the array satellites fail, observing by the rest of the array continues unhampered.

Observing Strategy

ALFA will observe in all directions continuously, at frequencies determined by solar emission during solar radio bursts, and at one of several sky survey frequencies during periods between solar bursts. Each satellite receives an X-band carrier from the ground station (to which the local oscillators are phase locked) and low-rate command telemetry, and transmits X-band data to the ground continuously at 0.5 Mb/s per satellite. The distance of the orbit and its location in the ecliptic plane allows continuous coverage of the array by three ground tracking stations.

Ground Processing

At the ground station telemetry headers are removed and the remaining interferometry data from each satellite are recorded on tapes for transport to the correlation computer. Small subsets of the data for rapid solar snapshot imaging will also be stored on disk and retrieved from the stations via internet. The DSN 11-m ground stations are currently operational, and operator intervention will be required only for occasional (once every several days) tape changes or in case of station equipment failure.

Array Configuration

Among the challenges of imaging the sky at low radio frequencies is the need to image the entire sky at the same time. This is necessary because individual radio antennas of reasonable size have very low directivity at these frequencies (which is the motivation for using an interferometer array in the first place). Consequently very strong radio sources will create sidelobes in directions far from their positions, and high dynamic range imaging will require that the effects of strong sources be removed from all sky directions, not just from the region immediately adjacent to the sources. This in turn requires an array geometry which produces highly uniform aperture plane coverage in all directions simultaneously, a requirement that no previous interferometer array has had to meet.

A quasi-random distribution of antennas on a single spherical surface was found to provide excellent aperture plane coverage in all directions with a minimum number of antennas. This concept was developed by Steve Unwin at Caltech, who noted the importance of using a minimum separation constraint when computing antenna locations to avoid an excessive number of short projected spacings.

3. MISSION DESIGN

The ALFA mission design meets the basic science investigation requirements for a stable mission orbit at a distance of at least 10^6 km from the Earth (to minimize terrestrial radio interference) and which can be reached at low launch and insertion energies to allow the mass for a 16-satellite array. A distant retrograde orbit (DRO) design [2] was selected from among several possible choices including heliocentric orbits and L1 and L2 Lagrange-point halo orbits. The selected DRO places the array well beyond the Moon's orbit. Using a segment of a periodic Earth-return orbit that arrives tangent to the DRO nine months after launch at the point opposite the Sun, a modest maneuver captures the ALFA carrier spacecraft with its 16 attached subsats (Figure 4 and 5). The subsats are then sequentially deployed to positions on a 100-km diameter sphere centered on the carrier spacecraft (Figure 6). The DRO is inclined three degrees to the Ecliptic and the initial orbit period can be adjusted to avoid eclipses and direct alignments with the Sun during the two-year mission.

Launch is planned using a Delta II 7425 launch vehicle, which can deliver 804 kg at injection. The launch date is completely flexible with a three-week launch period available in every month. There is ample launch mass margin (34%, 203 kg with contingency).

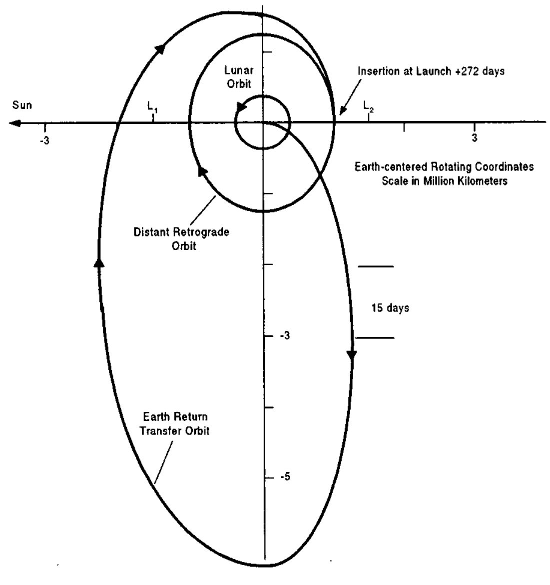

Figure 4 Low Energy Transfer to the ALFA DRO

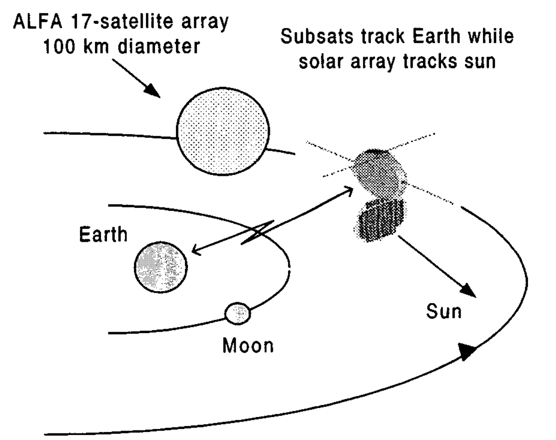

Figure 5 The Earth, the Moon and ALFA's DRO plus the Orientation of a Single Subsat

Array Deployment

Nine months after launch, the carrier spacecraft uses its hydrazine thrusters to slow itself into the DRO. To begin the data collection phase of the mission, the subsats are sequentially deployed and maneuvered to positions 50 km from the carrier to establish the 100-km diameter array of radio receivers. One month has been conservatively planned for this activity. Measurements of Doppler, from the ground, and intersatellite ranging are used to accurately position each subsat. A digital camera on the carrier allows assessment of proper subsat deployments after separation.

Table 3. ALFA Mission Summary

Mission Parameter	Value
Launch Date	July 1, 2002*
Launch Energy	0.154 $(km/s)^2$
Launch Declination	magnitude ≤ 26.5 deg
Transfer Orbit	Periodic Earth Return
Flight Time	272 days
Max. Earth Distance	5.8×10^6 km
DRO Insertion DV	134 m/s
Constellation Orbit	Distant Retrograde
Min. Earth Distance	1.0×10^6 km
Max. Earth Distance	1.2×10^6 km
Ecliptic Inclination	3.0 deg
Ecliptic Node (initial)	90 deg to Sun
DRO Period	94 days
Mission Duration	34 months

* Any launch month acceptable, but avoid lunar gravity effects (about one week per lunar month).

Array Maintenance

Maintenance of the geometry of the array requires careful measurement and control of each subsat position. To maximize the final radio image quality, the subsat positions need to be controlled to within 5 km of an assigned position on the spherical array. This requires each satellite to support a ΔV of 7 m/s over the 2-year mission, based on orbit and maneuver assessments by Microcosm Inc. and JPL. Highly accurate relative position and velocity measurements of each subsat will be obtained by a fixed-tone turnaround ranging subsystem on each subsat with an accuracy of <3 m.

For determining the array orientation, preliminary navigation studies at JPL indicate that combining Doppler with highly accurate intersatellite range data will provide very good navigational accuracy, sufficient to reconstruct the relative subsat positions to <10 m in an inertial frame

Intersatellite Ranging

A simple, well proven technique will be used to accurately determine the array configuration. Each subsat supports a fixed-tone turnaround ranging technique that is operational with Intelsat. By using four audio tones at frequencies of approximately 0.35, 2.83, 39.68, and 277.78 kHz, and sequentially measuring the range between all subsats pairs on ground command, we determine the relative ranges between subsats to better than 3.0 m. The tones are transmitted over a carrier (ISM band, 902 to 928 MHz) where no licensing is necessary (and signals are undetectable at Earth).

Navigation Backup

An alternate technique can determine the array inertial orientation by using observations of strong unresolved radio sources with known positions from higher-frequency, ground-based measurements. With these data, the geometric delays expected on each baseline can be calculated and compared with the measured delays. The difference depends on the error in assumed baseline orientations. This technique requires an additional manual step in data processing and either a wider range of cross-correlation delay offsets for each field of view or multiple passes of the raw data through the correlation computers. This technique provides a viable alternate approach to determining the array's inertial orientation.

4. SPACECRAFT IMPLEMENTATION

The ALFA array is implemented as a 16-subsat constellation, based on the Orbcomm design, plus a carrier spacecraft, which supports them from launch through deployment (see Figures 7,8, and 9). Orbital's experience in multiple satellite deployments includes Orbcomm deployments (up to 8 subsats each; Figure 10), the DARPA Microsats (7 subsats), and Stacksat (3 subsats). The ALFA subsats are stowed in four stacks of four based on the flight-proven Orbcomm design (Figure 9). A key element of each spacecraft is the implementation of non-coherent precision Doppler processing in the X-band transceiver. The use of this technique provides a low cost method for obtaining space-to-ground ranging data for each subsat. This technique, together with intersatellite ranging, will permit the reconstruction of the array orientation and the distances between each subsat

Both the subsats and the carrier are single string systems. The electrical power subsystem is based on the Orbcomm regulator, a small lithium ion battery, and a single GaAs solar array on a single axis that constantly faces the sun. The battery was sized to handle anomalous conditions. Science data will not be taken during eclipse conditions. The attitude control system uses a pitch bias momentum approach with an error signal from the X-band receiver together with a fine sun sensor providing attitude knowledge.

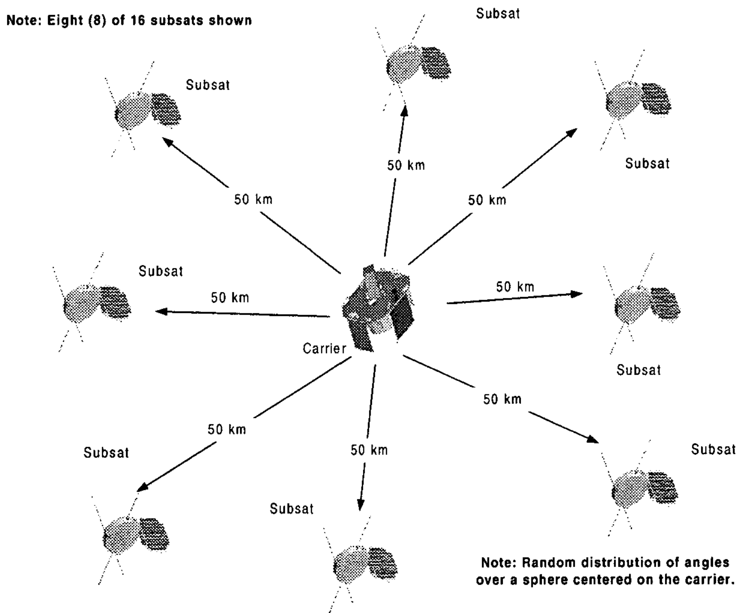

Figure 6 The Deployed ALFA Array (only 8 subsats shown)

Table 4. Spacecraft System Requirements

Requirement	Drivers	Req'd	Design	Unit	Margin
Maximum launch mass	Transfer orbit C3	601	804	kg	34%
Number of subsats	Image quality	12	16		33%
Subsat pointing control	HF antenna orientation relative to X-band uplink	± 2.0	± 1.0	deg.	100%
Link margin (500 kbps)	Data quantity w/coding	>0	3.2	dB	109%
Instrument power	Instrument operation	7.0	>15.0	W	100%
Instrument mass	Science return	2.26	>5.0	Kg	>100%
Radiation environment	Electronics ops	7.6	20	kRad	163%
Reliability (>90%)	Image quality	12/16-1 yr.	14/16-2 yr.	subsats	
Cold gas propellant	5km station keeping	0.312	0.6	Kg	92%
Hydrazine propellant	Carrier maneuvers	160	200	m/s	40%

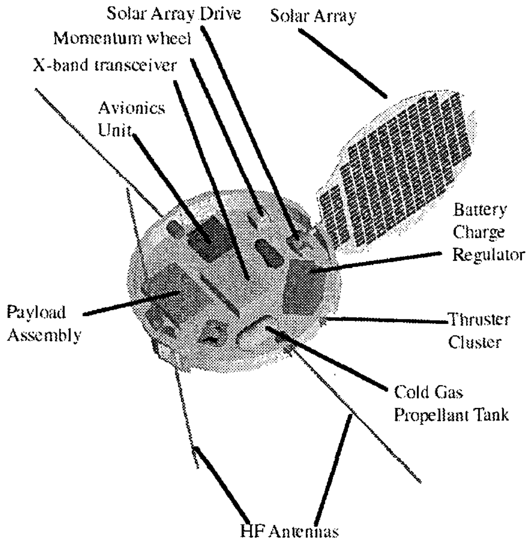

Figure 7 ALFA Subsat Top View

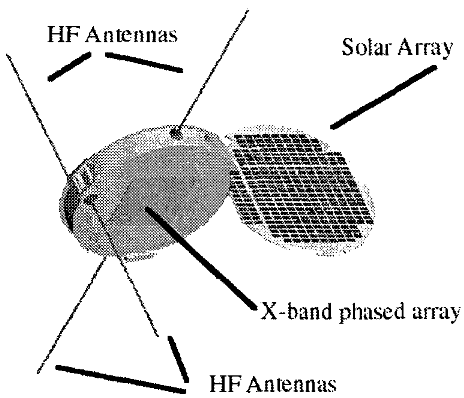

Figure 8 ALFA Subsat Bottom View

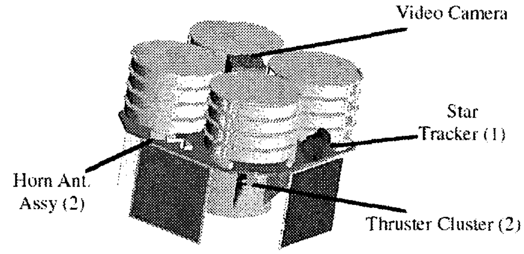

Figure 9 Carrier with Subsats Stowed

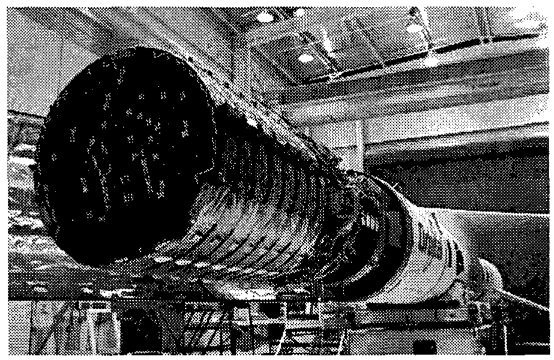

Figure 10 Orbcomm 8-spacecraft Stack being Integrated with a Pegasus XL

The ALFA mission is designed to be redundant at the system level: all subsats communicate independently with the ground, so no single subsat failure will be catastrophic. The design achieves all specified and derived performance requirements with large margins (Table 4).

5. CONCLUSIONS

ALFA is the first constellation designed for low frequency radio astronomy. The entire array operates together as an imaging interferometer. It is based on flight-proven, low cost spacecraft designs in volume production, a stable orbit, and the use of the low cost set of 11m DSN ground stations. The 16 identical array satellites are based on simplified versions of the commercial Orbcomm bus developed by Orbital Sciences Corp. There are currently 34 units on orbit with more under construction.

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