The ALFA Constellation Communications and Navigation Support System[1]

Regan E. Howard,
Orbital Sciences Corporation
20301 Century Blvd
Germantown, MD 20874
301-428-6091
howard.regan@orbital.com
Dayton Jones
818-354-7774
Dayton.L.Jones@jpl.nasa.gov
William Blume
818-354-7396
wblume@jpl.nasa.gov
Calina Seybold
Calina.C.Seybold@jpl.nasa.gov
NASA Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109-8099

Abstract - The proposed ALFA space-based imaging interferometer mission consists of 16 identical small satellites with dipole antennas and low frequency radio receivers, distributed in a spherical array 100 km in diameter, and 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. The mission communications and navigation support system consists of an X-band frequency division multiplex (FDM) TT&C segment that uses a common 50 bps uplink channel and 17 downlink channels of 500 kbps each. The TT&C segment supports non-coherent precision Doppler ranging. Intersatellite ranging in the navigation support subsystem is accomplished by using the common four tone ranging technique over a UHF channel in the ISM (Industrial Scientific Medical) band.

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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 30 kHz 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

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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 science goals are links 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. Table 1 relates the science requirements to the mission parameters.

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

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 1 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.

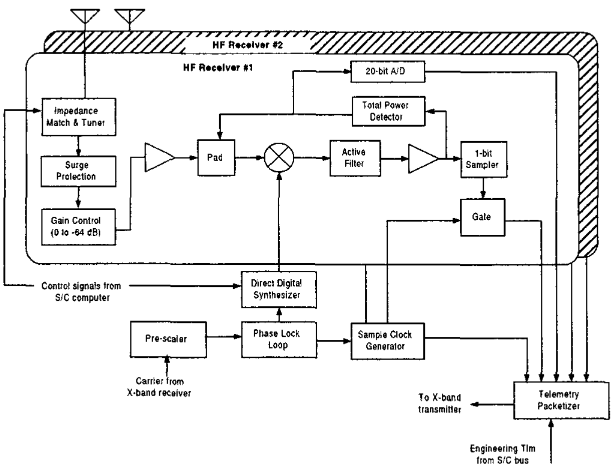

Figure 1 Low frequency payload receiver.

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 distant retrograde orbit (DRO) about the Earth-Moon barycenter [2], with a typical distance from Earth of one million km. There are many advantages of a DRO 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 (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 DRO and its location in the ecliptic plane allows continuous coverage of the array by three ground tracking stations. 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.

3. COMMUNICATIONS

To reduce tracking costs and resource contention with other missions, all communications with the ALFA carrier and subsats is handled through the DSN 11-m subnet. A single stable carrier X-band uplink will be used for all spacecraft, which are always within the main beam of the ground antenna. Individual subsats are commanded by unique subsat addresses in the commands. In the X-band TT&C scheme (Figure 2), each subsat transmits a 500 kbps, BPSK-modulated data stream onto its unique carrier. The spectrum plan in Figure 3 shows a single uplink carrier that is monitored by all spacecraft in the constellation. Commands are targeted to a particular spacecraft in the constellation by an address field in the command packet. On command, a selected spacecraft may be switched from data transmission to sending a non-coherent precision Doppler signal for navigation (see section 4). The 17 downlink signals are single channel per carrier that use OQPSK (Offset Quadrature Phase Modulation). The telemetry conforms to CCSDS standards including direct modulation of the carrier. There are no subcarriers.

Implementation of the ground network architecture requires the addition of a single 19" rack of equipment in each of the existing 11 m DSN stations. The equipment includes the following:

- multi-channel receiver
- 5 W X-band power amplifier
- phase modulator (BPSK)
- ground controller including Internet interface
- digital tape recorder assembly including cartridge management

The multi-channel receiver uses off the shelf high performance digital signal processing and downconverter modules.

While operational, each subsat requires a maximum of 100 commands/day for a total of 2800 B/subsat or a total of 44.8 KB/day. This is well within the capacity of the uplink. 100 bps S/C telemetry produces an accumulation of 17.28 MB/day, or 6.3 GB/year, which is readily accommodated by current storage technologies. Each of the three ground stations sees the 8-Mb/s science stream for 8 hrs/day on average. The 100-GB tape capacity means that tapes, one for each subsat, can be recorded for weeks, but are typically changed weekly. Table 3 presents a summary of the communications approach.

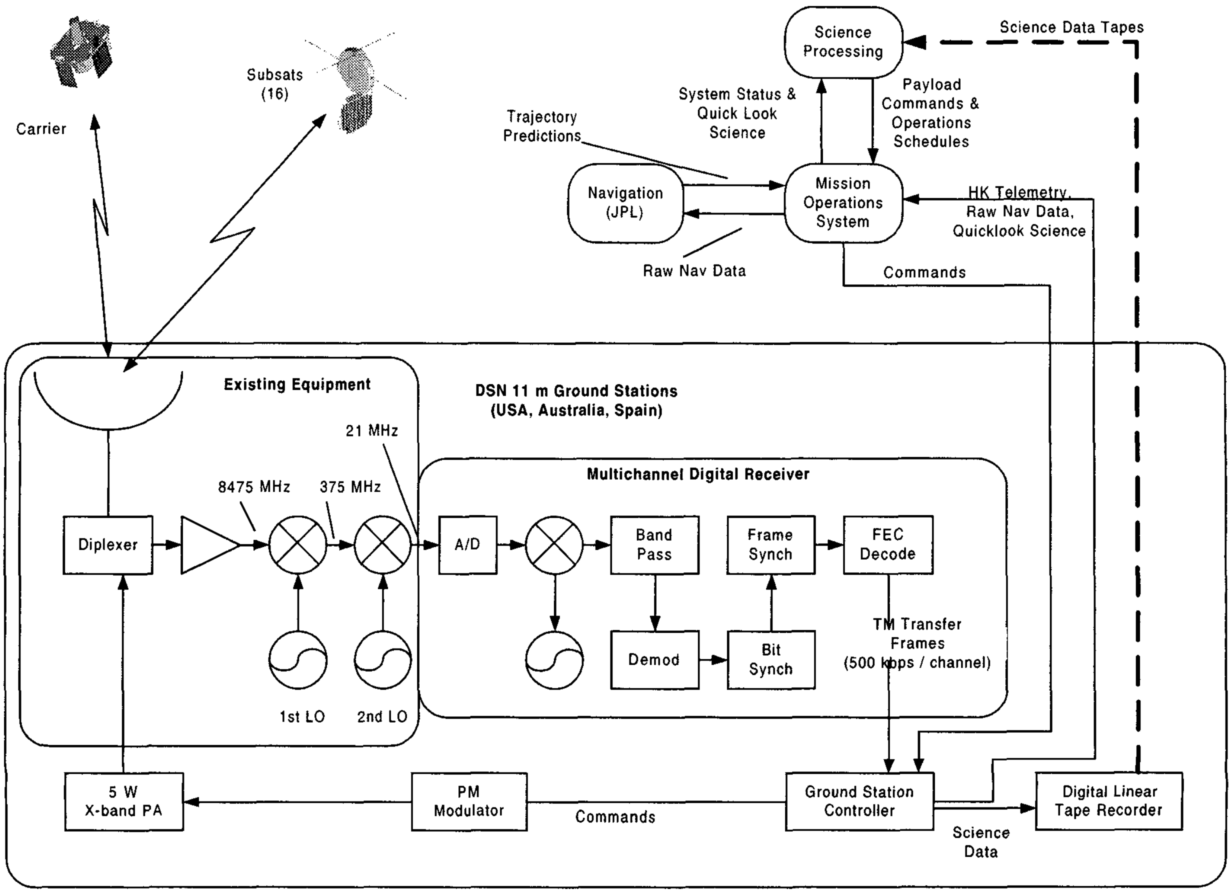

Figure 2 Communications Architecture

Licenses	JPL Spectrum Mgr.

Table 3. Communications Summary

Downlink	Value
Data Volume	86.4 Gbytes/day
On-board Science Data Storage	None
Downlink RF Power	5 Watts
Data Dumps	Continuous
Spacecraft Data Delivery	Orbital Mission Control Center via TCP/IP
Science Data to /Time Lag	JPL via tapes/10 days acceptable, GSFC quick-look solar burst data via TCP/IP /few hours
Uplink	Orbit maneuvers and P/L non-interactive commands
Uplink Frequency	2 per day (nominal)
Uplink Volume	545 Kbytes/uplink
BER	1.E4

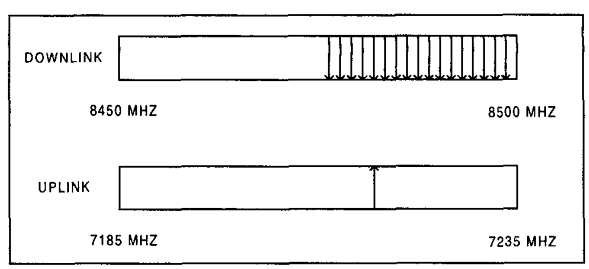

Figure 3 Frequency Plan

Subsat Communication Equipment

The ample margins and flight-proven components of the ALFA TT&C subsystem provide low risk communications and reduced ground operations costs. The X-band TT&C subsystem consists of three major components: an X-band receiver, an X-band 5W transmitter, and an Orbital phased-array antenna assembly that provides high-gain (29.5 dB) and medium-gain (10 dB) patterns. The medium-gain pattern of the antenna assembly is used to support uplink acquisition during deployment and after anomalies. The high gain pattern supports monopulse tracking which allows the spacecraft to lock on to the uplink and provide pointing knowledge to the spacecraft attitude controls system. The receiver and transmitter together support non-coherent precision Doppler tracking.

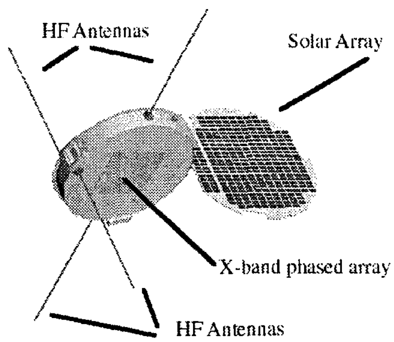

Figure 4 Subsat in Deployed Configuration

Carrier Communication Equipment

The carrier uses the same X-band TT&C subsystem as the subsats; however, instead of a phased array antenna the carrier has a medium-gain (10 dB) horn antenna assembly plus omni antennas. The horn assembly creates a fan beam pattern that provides the necessary link margin at the transfer orbit extreme range while the carrier spin axis is normal to the transfer orbit plane for thermal control.

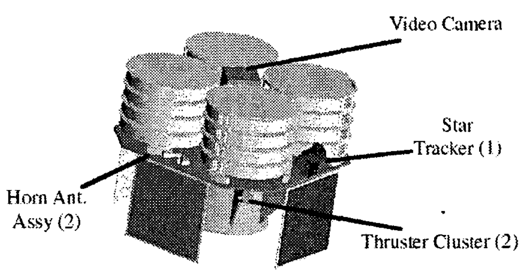

Figure 5 Carrier with Subsats Stowed

4. NAVIGATION

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 < 3.0 m. 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 3m. The tones are transmitted over a carrier (ISM band, 902 to 928 MHz) where no licensing is necessary (and signals are undetectable at Earth). The intersatellite ranging is performed on ground command between pairs of satellites with only one pair operating at a time. This method is valid given the slow interspacecraft dynamics.

For determining the array orientation, preliminary navigation studies at JPL indicate that combining ground-based 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

Doppler data between the 11 m stations and each of the spacecraft is obtained using the technique of two-way non-coherent precision Doppler (NCPD) [3] developed at JPL over the past 18 years. This technique was selected because it provides the necessary accuracy at reduced power, mass and cost over coherent techniques. Figure 6 provides a sketch of the on-board processing with the Doppler shift D determined from measuring f_r, the received frequency, f_1, the transmitted frequency and f_s, the difference between the two. From the three measurements and knowledge of the multipliers N and M:

$$D = \sqrt{\frac{f_s + (\frac{N}{M}) \cdot f_r}{f_1}}$$

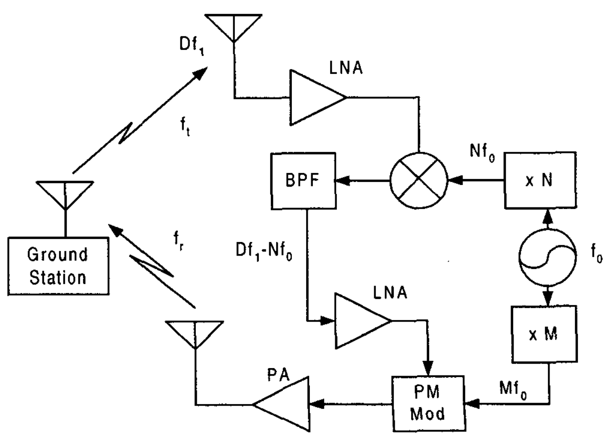

Figure 6 Non-coherent Precision Doppler Processing Overview

5. MISSION OPERATIONS

Primary ALFA mission operations responsibilities are divided between JPL and Orbital in their areas of greatest expertise (Figure 7). These are simplified by the simple operational plan with the subsats always Earth pointed, continuous DSN coverage, no data storage/playback, and one basic payload mode. Orbital, currently flying multiple Orbcomm satellites from its existing mission control center (MCC) at Dulles, VA, is the node for S/C analysis and control. JPL provides MOS management and the TMOD/DSN interface, science data processing and analysis (with the science teams), and the important navigation function. Orbital collects all S/C engineering telemetry and navigation data via Internet TCP/IP connections through the project unique racks at each 11-m DSS. Data is autonomously alarm monitored, processed, and stored at the MCC. A project dedicated team provides daily prime shift coverage for analysis and control and is backed up by Orbital's continuous MCC staffing. Additional technical staff is allocated at launch and deployment. Navigation and payload status data are quickly available for periodic downloads to JPL. Maneuver commanding is handled by Orbital from JPL ΔV computations, and noninteractive payload commands, mostly for selecting the sampled frequency bands, are checked and passed through in near real-time. JPL's role is overall MOS coordination, science data processing, and navigation. Tapes containing the high-rate payload data are shipped from each DSS weekly to the ALFA processing center at JPL for correlation. For solar burst monitoring, some quick-look data are captured by the project unique telemetry processor, based on a total power telemetry threshold, and stored until the next occurrence. This allows on demand downloads to GSFC for this science objective.

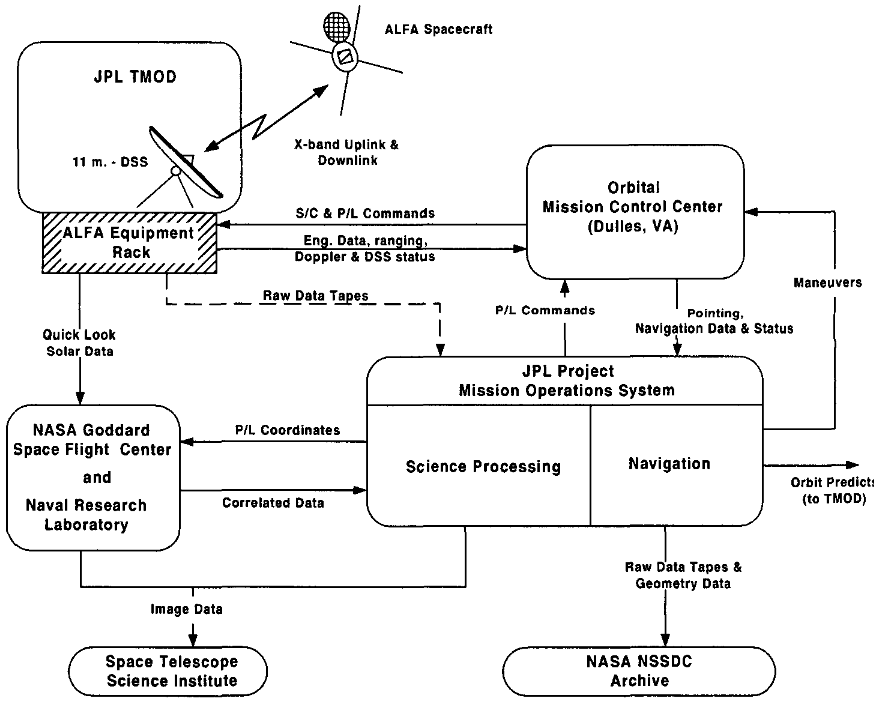

Figure 7 One rack of project unique equipment at each 11-m DSS provides fast access for low-rate telemetry, navigation data, and commanding and a simple tape interface for high-rate science data.

6. SCIENCE DATA PROCESSING

Figure 8 shows the science data flow for deep all-sky imaging (left column) and rapid solar snapshot imaging (right column). The solar snapshot images provide a way to remove the strongest and most variable sources prior to deconvolution. Note that the comparisons of the final images from both paths will be made between different software packages and different institutions to check for errors and insure the understanding of the level of accuracy in the images. This two-path approach to complex data reduction was used with great success by the Hipparcos mission.

In addition to the raw (uncorrelated) data, which will be sent to the NSSDC on tape, we will archive all of the correlated, calibrated data (as 30 minute averages) and all final sky images at each frequency in the Hubble Data Archive (HAD) at the Space Telescope Science Institute. The total quantity of raw data will be approximately 32 TB. This will require 320 advanced intelligent tapes (AIT) at current capacities. These tapes will be recorded at the DSN stations, transported to the correlation computer for processing, and then sent to the NSSDC. The total quantity of correlation data and images will be about 1 TB.

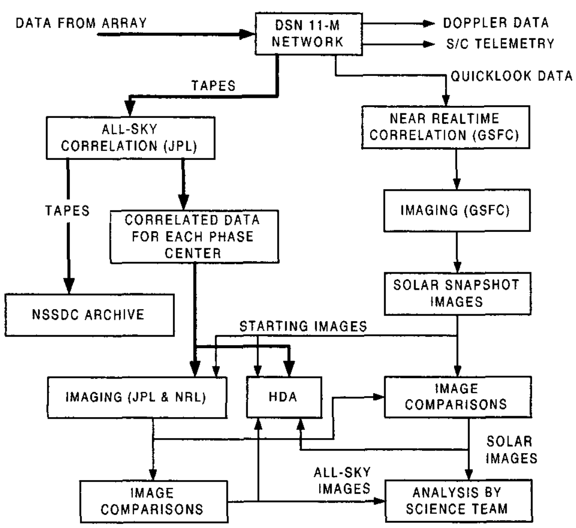

Figure 8 Science Data Processing Overview

7. CONCLUSIONS

The ALFA communications and navigation support subsystem is based on a robust architecture that makes use of the 11-m DSN antenna subsystem. Navigation is supported by a hybrid of non-coherent precision Doppler tracking together with fixed tone intersatellite ranging. The processing of mission information is performed by the mission elements with the appropriate expertise.

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[3] Bruce Crow, Private communication

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Regan E. Howard is a senior member of the technical staff in the Space Systems Group of Orbital Sciences Corporation. His work focuses on mission systems engineering and the development of mission and spacecraft concepts for NASA, DoD and commercial customers. Prior to this he held positions at CTA INC., Fairchild Space Co., Comsat Laboratories, and Westinghouse. He received his Ph.D. in engineering in 1975 from the Catholic University of America and his B.S. in Physics in 1971 from the University of Maryland at College Park. He is a member of the IEEE, SPIE, AIAA and the AAAS.

Dayton Jones received his Ph.D. in astronomy from Cornell University in 1981. He was a Research Fellow in radio Astronomy at Caltech from 1981-1984, and a National Research Council research associate at the Jet Propulsion Laboratory from 1984-1986. He joined the Astronomical Measurements Group at JPL in 1986, where he is currently a senior member of the technical staff. His research interests include radio astronomy, instrumentation, and aperture synthesis image processing. He is an author on more than one hundred scientific papers in refereed journals and edited conference proceedings, and is a member of the IAU, AAS, URSI, AGU, ASP, SPIE, and Sigma Xi.

William H. (Bill) Blume is supervisor of the Mission Engineering and Planning Group at the NASA Jet Propulsion Laboratory and mission design lead for the Deep Impact project, which started in fiscal year 2000 under NASA's Discovery Program. He has B.S. and M.S. degrees in aeronautical and astronautical engineering from Purdue University and 22 years of experience in mission design and advanced studies at JPL.

Calina Seybold has Aerospace Engineering degrees from the University of Maryland (B.S.) and The University of Texas at Austin (M.S. and Ph.D.). As an engineer at the Jet Propulsion Laboratory, she has worked on the mission design team for Mars Global Surveyor and as deputy proposal manager or mission engineer on several major mission proposals, including ALFA. Currently, she is on the mission design team for Deep Impact, a Discovery mission to study the interior of a comet nucleus.