Configuration Trades for a Space Object Surveillance Fence

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ABSTRACT. We examine the mission and requirements of space surveillance as currently met by the existing NAVSPACECOM VHF surveillance fence. Upcoming replacement cost considerations provide a cost offset for a new radar. A technology date of about 2002 provides a basis for a trade space that leads to a new configuration.

A summary requirement is to maintain the orbital object catalog of objects 30 cm and larger. An increasingly important but currently unfunded requirement is to provide alerting of collisions between debris and operational spacecraft, particularly high value, high risk space vehicles such as the International Space Station (ISS) and the Space Shuttle. Orbital objects as small as 1 cm are a threat to the ISS, the Space Shuttle, and other spacecraft.

The existence of a well thought out VHF fence supports development of scaled CW fence concepts, but sufficient investment in development of pulsed concepts is warranted to explore operational advantages. A 1 cm debris size and antenna cost considerations drive toward wavelengths of 6 cm or shorter, but an allocation in the 3 GHz region is underway. The bottom line is that we should reexamine the mission and requirements of space surveillance and reevaluate multiple solutions.

REQUIREMENTS. The space surveillance mission, simply summarized, is to support the catalog of orbital objects [1, 2, 3, 4, 5, 6, 7]. Currently, this catalog is about 9,000 objects [8]. Due to uncertainty in orbital elements of each object, maneuvers, breakups, and collisions, maintenance of this catalog is best met by a surveillance fence that sees most objects often. Derivative requirements such as Chambered Round are also stated, and met by such a fence [7].

Protection of the ISS and Space Shuttle from collisions with space debris is a known threat that is getting increasing emphasis [9, 10, 11]. Building in tolerance of debris sizes to about 1 cm in the ISS and Space Shuttle is deemed practical [9 p. 46], but the main protection against debris of larger sizes is tracking this debris and taking appropriate measures to prevent collisions. Since 1 cm debris will stay in 300 km to 450 km orbit from about a month to about a year before decaying, depending on the solar cycle [9, p. 31], debris in this size range must be detected reliably to 600 km altitude to provide data on a time scale appropriate to spacecraft mission planning and execution.

The number of space objects has increased linearly since about 1960 [6, page 20]. Due to international agreements on explosions and debris generating mechanisms such as explosive bolts, in place since about 1995 with most countries with launch capabilities, increase of space debris densities is now less rapid than in the past. Projected flux of debris objects is expected to remain at about 4×10^{-5} objects per square meter per year in the important orbital regime of 900 km altitude for another decade or two [6, page 171] but will inevitably increase after that time due to collisions between existing debris particles and resulting debris breakups.

WAYS AND MEANS TO MEET THE MISSION. Candidate sensors for space surveillance must include space based sensors as well as ground based sensors.

Candidate ground based sensor options, with feasibility issues, are

- Upgrade Existing VHF Surveillance Fence: The high altitude (high gain) receiver sites at Elephant Butte, NM and Hawkinsville, GA are key to the ability of the radar to achieve its best sensitivity. These antennas are large arrays of exposed dipoles. These antennas are scheduled for replacement in about 2002 due to the end of their useful life. This is a very expensive proposition and provides significant cost offset supporting a microwave upgrade concept. Similar issues with the O&M costs of the transmitter solid state modules and other issues will need to be addressed to keep significant capabilities. Bottom line: expensive life cycle replacements and similar issues require large expenditures in the 2002 time frame. A significant investment might reveal less expensive alternatives to keep part or all of this capability. But, the long wavelengths used mean that this radar will never be useful in detecting 1 cm debris at 600 km altitude.

- New Active RF: Several studies [12, 13, others] that open up the trade space for a new radar have shown that a microwave system can meet the mission with much smaller transmit antennas and simpler antenna concepts. This will be a new start development program. A wavelength of 6 cm or shorter must be used to maintain sensitivity for debris sizes down to 1 cm.
- EO/IR: Ground based EO/IR sensors have been used successfully to detect and track individual orbital objects for some time. However, the solid angle searched by an individual sensor is small, and an practical architecture for a search fence that does not allow fly-through is not obvious. An investment may reveal such a viable concept, but this sensor would necessarily not be all weather. Its best use seems to be as an auxiliary sensor with cueing from another sensor.
- Laser Radar: Lasers have been used to track individual objects to very high accuracies for some time. These sensors have the same problems in maintaining a high probability of intercept search fence as explained above for EO/IR sensors, both space and ground based.

Candidate space based sensor types, with feasibility issues, are

- Space Based Active RF: Average power limitations of solar powered satellites prevents full time long range detection. High probability of detection would require a large and thus very expensive constellation. Such a constellation would survey a limited altitude regime because of detection range limitations. An overall configuration that does not allow fly-through is not obvious.
- Space Based Passive EO/IR: For the purposes of orbital object surveillance, this type of sensor has a trade of sensitivity versus field of view for a given aperture size. An architecture that provides a fixed fan beam search fence is not Reasonable aperture sizes do not provide a viable search volume for a small constellation, particularly with uncooled focal planes. Again, we have a large, expensive constellation that would survey a limited altitude regime.
- Space Based Laser Radar: The Active RF discussion applies, with the added issue of beam size and object fly-through. Best use of laser radar is raster scan or windshield wiper scan, which would not provide high probability of detection for objects subtending small angles and having high angle rates at the sensor due to orbital object fly-through. A practical laser radar fan beam concept is not obvious.

Of these alternatives, three combinations survive the tests of viability in meeting the mission, affordable in cost, and low risk:

1. New Active RF. Economical pulsed concepts similar to a scaled version of the BMEWS AESA upgrade have difficulty with sensitivity and debris fly-through because of the small beamwidths necessary to keep sensitivity high and the high angle rates of LEO objects. Use of beam occupancy to perform verification and track to estimate six orbital elements exacerbates the fly-through problem, and an economical concept that does not involve more than one transmitter is not obvious. As a result, this sensor would seem to be a CW fan beam at microwave frequencies, and could be considered a scaling of the VHF surveillance fence. Sufficient investment should be made in pulsed concepts to determine if a competitive concept is available that will measure six orbital elements from a single site.

2. Retain Existing VHF Surveillance Radar. This option requires new technologies to solve existing O&M issues, particularly to reduce life cycle costs of the antennas.

3. Retain Some Existing VHF Capability, Add Microwave Fence. This approach would leverage some or all of the existing VHF fence to mitigate any schedule risk of the microwave fence and possibly reduce its development and life cycle costs. It might also supplement it by providing verification and track data for newly detected orbital objects. The microwave fence would still have to see 1 cm debris up to 600 km altitude to meet the requirement of protection of the ISS and Space Shuttle, and supporting cost offsets from standing down the VHF capability would be reduced.

REQUIREMENTS FLOWDOWN. The new capability must, in general, match or exceed the capabilities of the existing VHF surveillance fence and reduce costs. The fan beam must extend over 22.5 degrees of longitude arc at altitudes where high probability of intercept is required to prevent fly-through as the fence rotates with the Earth through an object's 90 minute orbit. Since the fan beam will cross the orbit every 12 hours as the Earth rotates, the radar will "see" objects at least twice a day. The product of the radar average power, transmitter antenna gain, and receiver antenna area must be on the same order as that for the detection channel of the existing VHF system to maintain the same sensitivity. Other configuration trades, such as fan beam thickness and dwell time, are also important.

The VHF fence was designed and configured in a time when minimum object sizes of 1 foot were the accepted requirement. This defined an absolute minimum frequency of 75 MHz and a center frequency of 150 MHz to keep 1 foot objects at the limit of the Airy region. This fence was begun at 108 MHz and later changed to 216.98 MHz. The absolute minimum center frequency for keeping any viable radar equation sensitivity for 1 cm objects is 2.4 GHz, and the Airy region limit for 1 cm objects is a center frequency of 4.8 GHz.

SMALLER ORBITAL OBJECTS POSE SPECIAL PROBLEMS. Small objects, from 1 cm to 10 cm in size, are of special interest in protection of space vehicles because objects of this size will penetrate or otherwise damage spacecraft on impact [9, p. 46]. Smaller objects are more common than larger objects.

Smaller objects are more subject to drag, and objects on the order of 1 cm in size at altitudes of 600 km and lower are subject to significant change in orbital elements over a single orbital period. Therefore, tracking them all may be impractical because ambiguities in association of detections 12 hours apart might not be correctly resolved to a high confidence level. In addition, a 1 cm object will decay from 600 km altitude to 400 km altitude (where it will be a hazard to the ISS and Space Shuttle) in a year during the low point in the solar cycle, and a few weeks at the peak of the solar cycle. These particles will decay from 400 km to reentry in about 10 days at the peak of the solar cycle and a few months at the minimum of the solar cycle [6 p. 29, 9 p. 31]. In a year, 80% of orbital objects in this size range at altitudes from 200 km to 600 km will decay to reentry and be replaced by orbital objects decaying from higher altitudes. Therefore, sensing 1 cm objects at 600 km is appropriate to maintaining an awareness of orbital objects in this size range. A multiple hypothesis tracker (MHT) or similar technology will be required to track most of them, and maintaining track of individual objects without special attention will become more difficult as its orbital altitude decays.

PRODUCING ORBITAL ELEMENTS ON FIRST PASS IS DIFFICULT. This requirement is difficult to meet with a single sensor while maintaining an unmodulated CW fan beam search fence, even with triangulation. This is because, even though the position can be obtained in three dimensions through two axis monopulse in two receivers, only two bistatic range rates are measured with an unmodulated CW waveform. Receivers in the plane of the fan beam can obtain velocity in this plane, but not velocity across the plane. This is 5 numbers, not the 6 that is required to define all the orbital elements of an object. Because high probability of intercept without allowing fly-through is deemed the more important requirement, the existing VHF fence was designed to produce 5 numbers. Since we can meet the mission with the VHF fence by using other sensors or waiting for a second detection by the VHF fence, the same relaxation of this requirement for the microwave fence may be allowable.

Because range rate resolution is better at higher frequencies at the same dwell, chirp rate of radar returns caused by the v^2/R relative acceleration allows a measurement of velocity across the plane of the search fence. The quantity v here is the crossrange component of relative velocity and the quantity R is the range to the target; minor complication accrues to bistatic configurations. This will be very helpful in the use of a microwave search fence but will not provide high accuracies because of the short dwell times from the thin fan beams necessary to keep transmitter antenna gain high.

Velocity normal to the fence plane can be sensed by a receiver site out of the plane of the fence. Such a site would have multiple preformed receiver beams in two dimensions to cover detections at different altitudes but would be otherwise similar to receiver sites in the fence plane.

The conflict in functional allocation between the detection and tracking requirements is a classical sensor problem and is sometimes met by the use of separate modes or even additional sensors. For example, the original 1960s BMEWS radars used separate horizon search and track radars, and the active electrically steered array (AESA) upgrades use separate modes. The BMEWS design prevents fly-through by controlling the revisit interval at each horizon search beam position while allocating sufficient beam occupancy to the track modes to meet its limited track objectives. This option is not available to the microwave RF sensor because the fan beam must be very thin to keep antenna gains high and orbital objects often exhibit high angle rates, and fly-through is unavoidable if the fence is reallocated for even one dwell.

The option of using multiple FM sine waves or other modulation on the waveform to measure range will produce all 6 orbital elements in a single pass, and this option deserves more study. Significant disadvantages of this approach include complications in the signal processing and additional difficulties in ambiguity resolution when a large number of objects is detected in a single dwell. These difficulties may be mitigated by advances in digital signal processing hardware over the life cycle of the new microwave sensor.

Use of a separate sensor is the best option. Often the object has been detected prior to its crossing the fence by another sensor and the data provided by the VHF fence completes the orbital parameter set at that time. When the VHF fence provides the first detection of an orbital object, the surveillance fence alerts the Space Track community and another sensor provides data that completes the orbital set of the new object, or the surveillance fence itself provides the second detection 90 minutes or even 12 hours later.

An additional pencil beam RF sensor could provide the verification and tracking function. Such an additional sensor could be a major cost driver. An X band cued, pencil beam ESA with a pulsed waveform would be an excellent choice for this sensor from the functional point of view.

An additional passive EO/IR sensor, co-located with the receiver sites, could provide a verification and track capability. Although not all-weather, a 1 meter aperture, cued to a line of sight by new detections, could serve this function at a very moderate cost. This sensor would be available for other uses when not required by the surveillance fence.

PRINCIPAL COST TRADE ISSUES ARE DRIVEN BY ANTENNA CONSIDERATIONS. In terms of fabrication cost, the most expensive items, by far, are the arrays and transmitter. Antenna life cycle costs dominate the overall cost picture of the existing VHF fence because of the large antenna sizes necessary and because these large antennas are made up of dipoles exposed to the elements. A microwave system will have smaller antennas. The necessity that the receive antenna effective area approximate that of the VHF system, to achieve comparable sensitivity, is achieved by the fact that the VHF system uses only one 1200 foot array for detection in the low altitude sites and two 2400 foot arrays for detection in the high altitude sites. Thus, the necessary receive antenna area of two 2400 foot VHF arrays is daunting but achievable. A microwave system will use all antennas at a given site in multiple preformed beams for detection to meet sensitivity requirements. Thus, the natural scaling of receiver antenna length normal to the fence plane while multiplying the number of antennas along the fence plane, both in proportion to wavelength, preserves sensitivity if all of the receive antennas are used to form multiple preformed beams for detection. Thus, the effective antenna area for a microwave receiver site is that of only the detection antennas at the VHF sites, not the area of all the antennas at a VHF receiver site, and very significant gains in antenna size are achieved. The smaller microwave antennas will be protected from the elements and will have entirely different O&M and life cycle support schemes.

Transmitter cost is also a significant cost issue, though far less so than antenna cost. The existing VHF main transmitter radiates about 750 kW, and a similar average power will be required of a microwave site to maintain the sensitivity of the existing VHF capability.

The cost of prime power for the transmitter is a significant O&M cost. The state of the art of DC to RF efficiency is 20% to 30%, and this range is seen in all sizes, including solid state transmitters, and shows no major variation with frequency.

Phase matching of the antenna elements can be considered a feasibility or risk issue. For microwave antennas, the use of multiple line antennas makes phase matching in a given line antenna a design issue, but phase matching at the receiver sites for multiple parallel antennas determines their ability to perform accurate direction finding in the plane of the fence. This phasing problem scales with frequency and there is no strong effect versus frequency.

Digital signal processing effects do vary quite significantly with frequency. As a rule of thumb, the processing load is proportional to the bandwidth processed, which in turn is proportional to frequency for a CW surveillance fence of a given fan beam thickness. The use of multiple preformed beams in a digital approach requires that separate receivers be used at each receiver antenna, multiplying the requirements for data acquisition and digital signal processing, again in proportion to center frequency. Signal chirp is neglected in the current VHF fence but cannot be ignored at higher frequencies, again multiplying digital signal processing in proportion to frequency. The number of objects “seen” by the radar also increases with frequency, this effect having a law that exceeds linear multiplication in proportion to center frequency. In spite of this daunting case for large processing requirements, processing is distributed among receiver antennas and is thus inherently parallel to some degree, and current COTS processing capability is well up to processing the bandwidth from each antenna at any center frequency under consideration.

Data processing is another factor that increases with frequency due to the increase in the number of objects. Currently, data processing is done in Dahlgren, not at the sites, which raises data flow architecture issues because of the effect of increased data generated at the sites. These overall architecture issues are unresolved.

<u>BANDWIDTH REQUIREMENTS ARE NOT A MAJOR DRIVER.</u> Bandwidth is a very real cost. Although bandwidth cost is not part of the POM or dollar amount allocated to development or design, this cost is part of the system cost and is taken into account to provide a balanced system engineering design with true cost accounting in the measures of merit used to evaluate center frequency trades. Orbital objects can exhibit both opening and closing velocities approaching escape velocity, 11.18 kilometers per second. This means that the Doppler bandwidth requirement is about $1.49 \cdot 10^{-4}$ times the center frequency. This is about 32 kHz for the 216.98 MHz VHF fence, 447 kHz at 3 GHz, 716 kHz at 4.8 GHz, and 1.5 MHz at 10 GHz. Clear bands of this size do not exist except for the current NAVSPACECOM allocation for the VHF fence, and making way for a new microwave fence will necessarily impact existing allocations. The cost of this impact increases with the bandwidth cleared for the new system. However, a bandwidth of 1.5 MHz for a radar of this importance should not be prohibitive.

One possibility to reduce bandwidth requirements for a new microwave capability might be to use part or all of the existing VHF fence to provide surveillance of high range rate objects to reduce bandwidth requirements of a new microwave capability. This is attractive because high Doppler objects are in orbits with very high eccentricity. A disadvantage may be that small debris in such orbits decays more slowly than small debris in near circular orbits and would not be seen reliably with a narrowband microwave fence, but such objects have a combination of low radar cross section (RCS) and high altitude over a high percentage of the time, and, as such, have a low probability of detection with any sensor. A narrowband microwave sensor will still see these objects when they pass through its fence plane near perigee.

DRAFT CONCEPTS. Pulsed fan and pencil beam concepts have not been sufficiently explored to prove out the attractive option of detecting and measuring six orbital elements in a search fence. A pulsed concept will meet the mission and requirements if

- A fan beam is used for search (scanning pencil beams would allow fly-through)
- Receive while transmit is done to prevent fly-through
- The fence is not perturbed by the use of RF assets to perform verification and track.

A CW fan beam fence will meet the mission and requirements if

- An unmodulated CW waveform is used
- The fence is maintained continuously
- The sensitivity is similar to that of the existing VHF fence
- At least two receiver sites are used, and
- An auxiliary sensor or other sensors are used to complete the orbital parameter set for newly detected objects.

Orbital debris down to 1 cm at altitudes of 600 km and below will be reliably detected if the center frequency is above about 4.5 GHz, depending on other radar sensitivity drivers such as average power and antenna sizes.

A single receiver site can perform detection but will only compute two direction cosines and a bistatic range rate, so two receiver sites are necessary to compute a position by triangulation. The two bistatic range rates computed allow computation of object velocity in the plane determined by the object position at the time of detections and the receiver phase centers (the fence plane, if both receivers are in the fence plane), but velocity normal to this plane is estimated only by the chirp rate of the signal (a sign ambiguity remains in this computation), which is less accurate than the bistatic range rate measurements. A third receiver site out of the fence plane will allow computation of all 6 orbital parameters if all three have good signal to noise ratio (SNR); this receiver will require additional complexity in signal processing over that of receiver sites on the fence plane because this site must form beams directed to different orbital altitudes.

The full orbital set will be obtained on the first pass by the use of separate sensors. As an example, the AN/FPS-85 Space Track Radar at Eglin AFB, one of the PAVE PAWS sites, or one of the Phillips Laboratories CONUS EO/IR sites could be used as a verification and track sensor for the existing UHF fence. Figure 1 at right shows the radar field of view (FOV) of all active Space Track sensors for orbital objects at 500 km altitude, and Figure 2 shows the EO/IR field of view. The data from these sensors could come before or after the first detection by the CW fence. Waiting for the next detection by the CW fence is an attractive option when quick response is not imperative and is often done with the existing VHF fence. The next detection usually comes on the next orbit, typically in about 90 minutes, but will nearly always come within 12 hours when the Earth's rotation moves the fence across the object's orbit again.

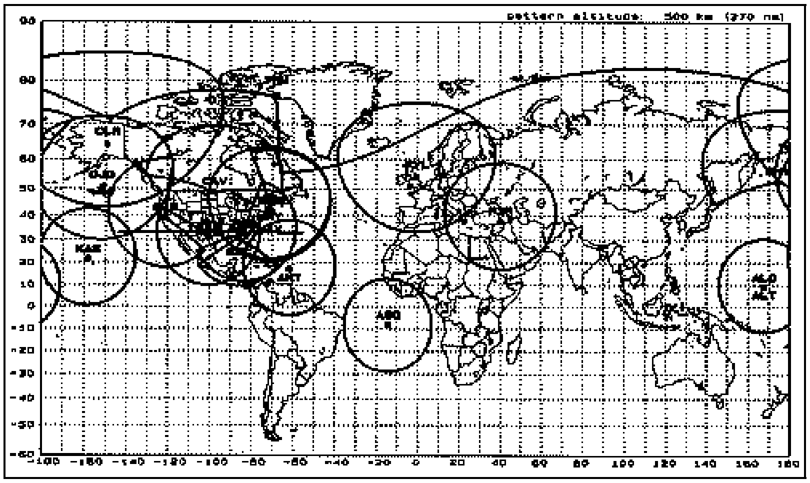

Figure 1. Space Track Radar Field of View at 500 km Altitude (From http://www.fas.org/spp/military/program/track/overview.htm)

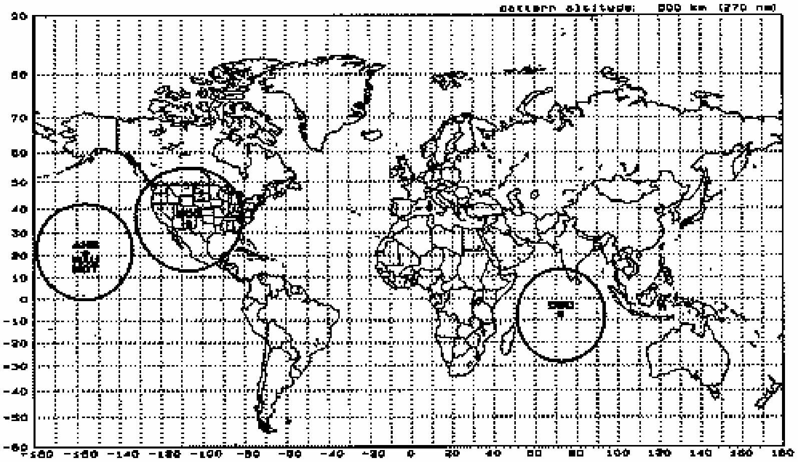

Figure 2. Space Track EO/IR Field of View at 500 km Altitude (From http://www.fas.org/spp/military/program/track/overview.htm)

An auxiliary EO/IR sensor could provide verification and track of new detections. A 1 meter reflector sited at one of the receiver sites would be cued to a line of sight and reacquired and track for a few seconds to provide a complete orbital set. Cost of this type of sensor is moderate relative to other system costs.

The bandwidth allocation of the new microwave fence can be reduced if part or all of the existing VHF fence is used to detect objects in highly eccentric orbits. Small debris in highly eccentric orbits would be seen by the microwave fence when it crosses its fence plane near perigee.

A pulsed RF sensor can be used for verification and track. Most current work [12, 13, others] has focused on CW sensors, and a reexamination of pulsed RF concepts with a 2002 technology date may result in a practical design concept that meets overall requirements.

<u>STRENGTHS OF THE DRAFT CONCEPTS.</u> The main strengths of the draft microwave CW fence concept include low risk and moderate initial cost. Relative to the current VHF surveillance fence, the draft microwave CW fence has improved orbital element accuracy and improved life

cycle cost. The microwave concept meets the mission in much the same way as the current CW fence, since it is essentially the same concept but scaled for frequency. The smaller antennas convey major simplifications in cost and siting considerations. The higher frequency allows some estimation of a 6th orbital element when detections are made from two or more sites placed in the fence plane, and a third site out of the fence plane would allow estimation of all 6 orbital elements on the first detection. A center frequency above 5 GHz and sensitivity at least equal to the current VHF fence will allow monitoring of 1 cm debris at 600 km altitude, so that density and orbital elements of debris at 400 km (typical ISS or Space Shuttle mission altitude) can be accurately predicted over time scales appropriate to planning and execution of missions.

<u>ISSUES OF THE DRAFT CONCEPTS.</u> Unless the center frequency is at least 5 GHz, utility in protection of the ISS and Space Shuttle from 1 cm debris is in question. Frequency allocation for a band at 3 GHz is underway, but the bandwidth currently obtained is sufficient for an initial capability but not wide enough to observe the same range rates as the current VHF capability. Frequency allocation at 5 GHz or above are deemed more difficult than at 3 GHz and are not underway at this time.

Operation of a receiver site co-located with the transmitter site is an attractive option since sufficient isolations are obtainable at microwave frequencies, and CW air defense systems using co-located receivers have been deployed. However, in heavy rain, scattered transmitter energy may cause severe spurs in the receiver due to dynamic range limitations. In cases of high object density, this may cause resolution of ambiguities to fail. This makes co-location of one receiver site with the transmitter a less attractive option.

Maintaining sensitivity as frequency changes requires that the effective receiver antenna area not change significantly with frequency. For antennas with fixed steering, cost per element does not follow a smooth curve with frequency because antenna concepts change. Receiver antenna cost does, in general, decrease with increasing frequency, but antenna cost must be carefully examined for any given concept.

The wider bandwidth requirement, and the fact that the new system will “see” about an order of magnitude more objects than the current VHF fence, raise issues of processing and data communications architecture. The simplest solution is full time high data rate links to Dahlgren and Cheyenne Mountain, which may become a cost issue.

The new sensor can obtain 6 orbital elements on the first pass when detections from two or more receivers is obtained with good SNR and signal chirp data is used. A North-South sign ambiguity remains, and accuracy of the sixth parameter is not as good as the others because of the short dwell times. A third receiver site out of the fence plane can obtain the sixth parameter with good accuracy, but with significant system complexity impact for that receiver site. The best option, at least for the near term, appears to be the use of other Space Track sensors of opportunity to perform verification and track of new detections, as is now done with the VHF fence.

The requirement to obtain 22.5 degrees of latitude coverage to prevent fly-through by objects with a 90 minute orbit determines the width of the fan beam. To obtain 22.5 degrees of coverage at 400 km altitude requires a fan beam width of about 140 degrees for a transmitter at a latitude of 33 degrees. Coverage at 600 km altitude requires about 125 degrees.

Most work to date has been on the trades associated with microwave concepts scaled from the existing VHF fence. Broader investigations that include pulsed or modulated CW waveforms and other differences and innovations can only strengthen the system concept development process.

<u>WHAT ABOUT KEEPING SOME EXISTING VHF CAPABILITY?</u> The VHF fence is in place with its frequency allocation, infrastructure, and data transfer architecture. Less visible capabilities such as off-line analysis of detection anomalies are part of the existing capability. Continuing the VHF capability for at least a few years allows overlap with the new microwave capability,

mitigating any schedule gap risk in meeting the mission. After examination of experience and the capabilities of both sensors and reformulation of the concept of operations (CONOPS) of the use of the sensors, a decision could be made to keep a portion of the VHF capability.

The disadvantage to keeping the VHF capability is that its best use is with the high altitude receiver sites in Elephant Butte, NM and Hawkinsville, GA. The antenna life cycle replacement due at these sites in 2002 represents a major part of the cost offset for the new microwave fence, and without these sites the argument for keeping the VHF capability is less compelling. Even at its best, the VHF site is less capable than a microwave fence in obtaining 6 orbital elements on the first pass.

Complementary usage of the VHF and microwave sites is an option. This option would be to use the microwave fence at a slightly different latitude than the VHF fence so that detections would occur closely spaced in time from the two fences. Each sensor would use the other to obtain the 6 orbital elements on a single orbital pass. This would relax the requirements on the FPS-85 and allow downing this system for technology retrofit.

Keeping the VHF capability, in part or in whole, requires that its life cycle and O&M cost issues be successfully addressed. This will require some investment. For example, a new receiver antenna concept that is both less expensive, and does not have a total replacement design end of life, is required to mitigate operating costs. The VHF antenna modules, in spite of their design being part of the very successful and reliable family of solid state AESA modules used in PAVE PAWS, BMEWS AESA upgrades, and ROTHR, have a unique environmental problem in that they are unprotected from the elements and temperature cycle over a wide range; resulting related O&M issues should be solved. Antiquated power supply capabilities need to be replaced with new designs, and other technology retrofits need to be applied.

<u>CONCLUSIONS.</u> In the light of the fact that a frequency allocation at 3 GHz is underway, a reasonable plan is to field a single microwave transmitter using this 3 GHz frequency allocation, a single receiver co-located at this site, and to use one of the sites currently used as a VHF fence receiver site to take advantage of existing data communication capabilities. An auxiliary EO/IR sensor at this site would complete facilities required to take full advantage of initial microwave fence capability and develop the experience necessary to maximize returns on investment on maturing this capability. This would be a first capability, and the concept would be reviewed before proceeding. The VHF capability will be fully maintained until the new microwave site is in place, allowing the planning for transition to the new capability to adjust to information gained in use of this initial capability. Baseline concept changes, resiting, center frequency changes, and other improvements will then be implemented as appropriate.

Phillips Laboratories, NRL and NAVSPACECOM have recently completed top down studies. Although the results of the Government studies are not public and thus did not contribute to this report, it is likely that many of the recommendations of these studies do agree with many of the points made here, and with those of the NAVSPACECOM studies [12, 13]. At this point, it seems advisable to consider these steps:

- Reexamine the mission, requirements and CONOPS using the results of the funded studies and other recent data, particularly the (at present unfunded) NASA requirement for detecting 1 cm debris,
- Consider mixes of sensors over the next 5, 10, and 20 year periods,
- Open up the concept to include pulsed concepts, modulated waveforms, and innovative new concepts,
- Develop detailed architectures to be made available at specific times in the near term, and
- Follow results of timely properly funded planning exercises with a definition of a specific concept for implementation.

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