Remote Control Southern Hemisphere SSA Observatory

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Abstract

EOS Space Systems (EOSSS) is a research and development company which has developed custom observatories, camera and telescope systems for space surveillance since 1996, as well as creating several evolutions of systems control software for control of observatories and laser tracking systems. Our primary research observatory is the Space Research Centre (SRC) at Mount Stromlo Australia. The current SRC control systems are designed such that remote control can be offered for real time data collection, noise filtering and flexible session management. Several fields of view are available simultaneously for tracking orbiting objects, with real time imaging to Mag 18. Orbiting objects can have the centroids post processed into orbital determination/ orbital projection (OD/OP) elements. With or without laser tracking of orbiting objects, they can be tracked in terminator conditions and their OD/OP data created, then enhanced by proprietary methods involving ballistic coefficient estimation and OD convergence pinning, using *a priori* radar elements. Sensors in development include a thermal imager for satellite thermal signature detection. Extending laser tracking range by use of adaptive optics beam control is also in development now. This Southern Hemisphere observatory is in a unique position to facilitate the study of space debris, either stand-alone or as part of a network such as Falcon. Current national and international contracts will enhance the remote control capabilities further, creating a resource ready to go for a wide variety of SSA missions.

1. History of Mount Stromlo SSA Research and Development

SLR Heritage

Since its creation in 1986, EOS has been a laser ranging oriented business, starting with satellite laser ranging from the Australian Capital Territory's Orroral site, and expanding to Germany, Saudi Arabia, Japan, and Mount Stromlo near Canberra. It is primarily a ground-to-space research company.

Space Debris Laser Tracking History

A theoretical study was commissioned in 1998 to evaluate the possibility of generating laser returns from Lambertian scattering sources in space, objects without the $1/r^2$ benefits of retro reflectors, having instead $1/r^4$ losses. The study concluded that for Near Earth Orbit space debris, laser tracking was theoretically possible if the object could be held stably on the laser boresight. Funds were sought from 1999, but the industry response at the time was sceptical. Capital was invested in a prototype minimal system sharing the new Mount Stromlo SLR station, and first space debris laser returns were obtained in 2000. However, this system was barely capable, highlighting the many challenges for the new industry.

Sensor Developments

Poor quality orbits are a key challenge for laser tracking of space debris, and in 2000 the station began an upgrade program of sensors to improve detection, correction of first order path aberrations and autoguiding. Initial tests were promising, with ranging success growing from 1% in 2000 to 25% in 2002. The program was amended in 2003 when wildfires destroyed the site, and a full rebuild was undertaken. First laser returns were obtained within 12 months of the fire, and new sensors for tracking and autoguiding on sunlit orbital debris were developed. The new equipment successfully laser tracked 50% of selected objects between 0.07m and 0.35m in 2004.

Latest generations of sensors cover many fields of view, with terminator phase detection capability of some 10cm objects at 900km altitudes (albedo dependent). Detectors for use outside of terminator phase are discussed below.

Current Studies: Orbital Analysis

The orbital element accuracy traditionally available is a challenge for the entire SSA community. New radar installations will overcome these problems gradually, as global budgets allow. Meanwhile, EOS studies the existing data to determine what can be mined from it to enhance current elements, For example, their decay and perturbation characteristics can be used to define a ballistic coefficient accurately, which can be included in current vector projections, to give improved Orbital Predictions (OP) based on any current Orbital Determination (OD) measurements. Where orbital conjunction analysis is important, the validity of parameters such as ballistic coefficients is critical to OP accuracy. Refer to separate papers submitted to this conference.

Complex Observatories and Control

Since 1996, EOS has made several control systems for its automated observatories, handling network management, site control and mission control with minimal or no operator input. However, the clear lesson learned has been that complex systems readily become tied up in their own logic, and this congestion and fragility leads to such control systems becoming “geriatric” and incapable of further development.

Therefore, EOS Space Systems has developed a control system since 2006 which has specific goals related to longevity, extensibility and flexible function. It is in effect an industrial control system which allows for any observatory mission to be facilitated. Separate papers are available which describe the successful architecture, generated after multiple previous designs reached their capacity limits and were abandoned.

Already, the new architecture enables the site to be turned over to remote users via Internet, with tasking by file transfer and real time monitoring of video feedback to confirm correct system responses. Moreover, the control system is deliberately designed to be adaptable for new missions, new hardware systems and new users. Re-usable and extensible modular design allows flexibility without binding up of the code base which has been a problem in earlier systems.

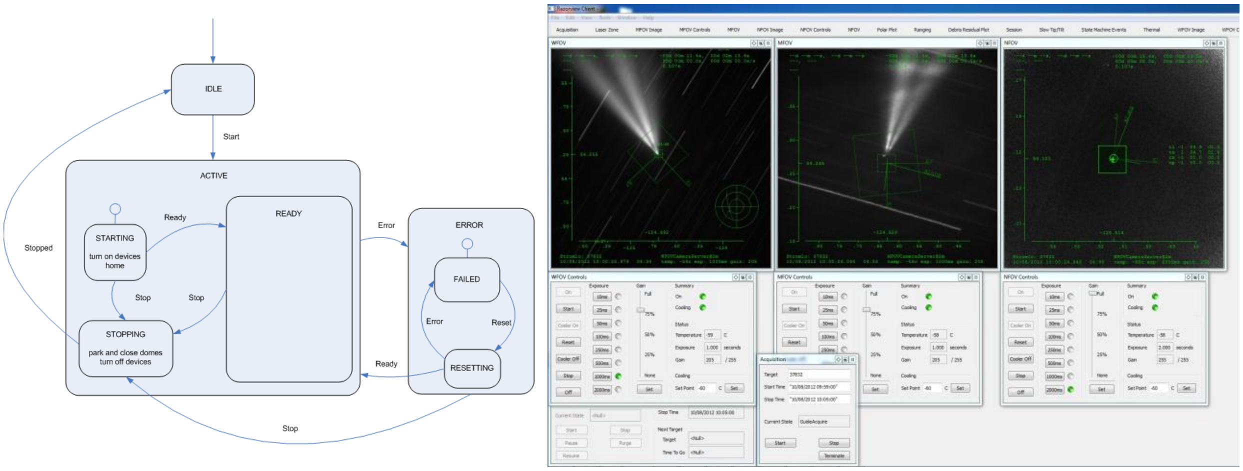

Fig 1: Architectural redesign has resulted in a powerful development base for any SSA observatory

Next Steps: SSA Network Potential

A site designed for customised control interfaces is potentially useful in the global SSA effort. Collaboration by the use of a local site support team and a visiting operations team are typical uses of the Mount Stromlo facility, as is common around the world. This traditional method is expensive, inefficient and has limited appeal. Sending a remote client application and VPN access file to any international user has made the use of EOS’ Space Research Centre facility much simpler.

Once the Space Research Centre site has been tested successfully as a prototype, its control architecture will be suitable for adaptation to a hypothetical wider network of coordinated sites, designed for harmonised long-arc tracking of space debris. 72 hour orbital predictions within 100 arc seconds accuracy are proposed, based on current OD/OP studies completed by EOS Space Systems.

By using an optical observatory network, older radar systems would then be able to cue the more accurate optical tracking network when potential conjunction risk is identified, extending the useful life of current radar systems for many years. In the current world financial climate, delays to the newer space fence network make the enhancements above more appealing. EOS Space Systems has long desired a cooperative optical SSA network, and wishes to see suitable specifications created.

The prototype remote controlled system is currently being tested and reviewed by one of EOSSS' international customers, to validate extension to a network of new or adapted optical observatories.

2. SSA Hardware Suite

Telescope

Space debris and SSA observations require accurate tracking of an optical axis onto the sky, to within 15 microradians. Once this is done, the tracking of objects must be smooth at speeds up to 1 degree per second. Additionally, fainter objects with weak solar scattering require a large collecting aperture and/or a pixel scale of >5 microradians (1 arc second) per pixel.

The primary Mount Stromlo instrument is a 1.8m Alt/ Az system in a co-rotating dome which places a working observing floor on the rotating azimuth reference frame. Auxiliary instruments and support equipment may be readily assembled adjacent to the telescope while it is operating, without the need for complex cable wraps. Typical sky calibration accuracy is <10 microradian.

Fig 1: 1.8m telescope with co-rotating observing floor

The 1.8m aperture is fed to a Coudé path for laser tracking with single photon APD detectors at 1064nm. A clean room is housed next to the observatory in the figure above, and maintains a steady environment for experimental equipment. Other visible wavelengths are fed to an imager for autoguiding with jitter of 1 arc sec rms, most of which is due to changes in the line of sight air column during tracking. Tracking smoothness is typically less than 0.1 arc sec rms.

Mounted on the main telescope are two small aperture wide field imagers, each with pixel scales preventing oversampling of the seeing limit, to achieve maximum sensitivity. EMCCD sensors are used for best signal to noise ratio in object detection.

Fig 2: Ultra wide field imager and mid field imager at Mount Stromlo

Poor elements are not a problem once the wide field sensors identify the object and pass offsets to the control system – the object is typically locked onto the main telescope optical axis within 20 seconds. Using laser tracking techniques, the site centric coordinates of the object can be obtained directly and stored for geocentric OD calculations after each pass. Even when laser tracking is not feasible due to poor link strength, passive collection of object position has been shown to be a valid technique for generating orbital elements at useable accuracy. Detailed explanations are contained in the associated papers submitted to this conference.

Detectors/ Sensors

Wide field sensors are a key component of any SSA system which must use poor elements. The EOS sensors have accounted for this by using two or three imagers simultaneously, mounting custom designed cameras to the main telescope Optical Tube Assembly (OTA). The use of cooled EMCCD imagers allows real time exposures of 10msec to 3,000msec, and fields of view are available from 300 arc seconds to 10,000 arc seconds (1,500 to 50,000 microradians). Compromises are accepted between sky noise per pixel on the widest fields, and oversampled seeing limits on the narrowest. In good conditions all imagers can detect to V_m 17, and some to V_m 18.

Cooled EMCCD devices offer the advantage of speed. Using gains of 500x to 1000x, the exposure times drop accordingly, and provide images in milliseconds rather than many-seconds. The trade-off is in higher contrast because of the ease of saturation from brighter sources, such that photometric measurements are not possible with EM gain. The imagers usually function as detectors, and therefore the contrast enhancement is a benefit rather than a hindrance in these missions.

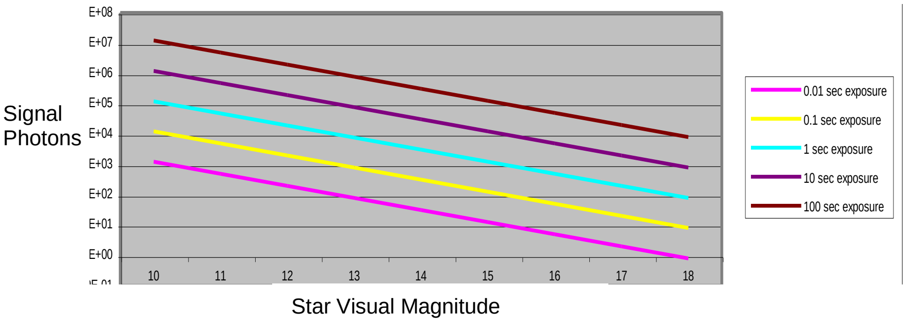

Fig 3: design analysis for EMCCD based sensor - visual magnitudes to 18 are achievable in real time

By comparison with older ICCD technology, the shot noise effect showing as random “snow” is much lower in EMCCD devices, but responds well to temporal filtering of multiple frames by pixel, when operating at highest gains. Similarly, LEO tracking creates star streak noise, which can be post processed by filters to enhance point sources, and GEO tracking can benefit greatly from optimised expose periods and temporal filtering to remove slow moving stars. EOSSS is experimenting with a variety of software filters to enhance signal to noise ratio in cluttered environments.

Laser Tracking

Early tests of space debris laser tracking showed that a few hundreds of Watts of pulsed laser energy are sufficient to generate returns for objects up to 1,500km away, despite the 1/r^4 link budget challenges. Object albedo and plate angle are variables not controlled, so results vary significantly. Detection range gate limits and autoguider stability are also key performance determinants, which are related to the accuracy of the initial elements. For more tolerance of autoguider lock quality and small object tracking, EOS Space Systems is now testing a kW scale pulsed laser.

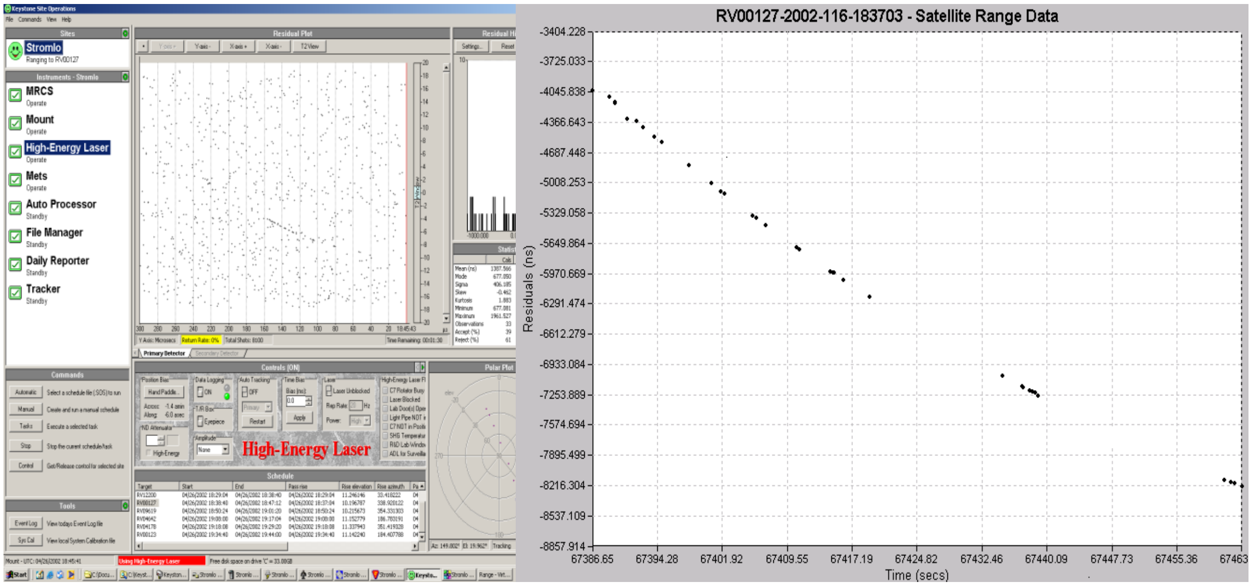

Fig 4: First reliable laser tracking of space debris, Mount Stromlo 2002

The limit to pulsed laser energy is always the management of damage thresholds for optics in the unexpanded beam path. Several techniques are being trialled now to obtain enhanced cleanroom classification in this high risk zone, with controlled costs of infrastructure, and without restricting maintenance access. Pulse handling is also being studied and enhanced, using vacuum relay tubes and Stimulated Brillouin Scattering techniques to obtain the desired fast rise times without suffering from the problems of having a high peak pulse power over 1 GW/sq cm.

3. Remote Control Capability

Heritage

The first high complexity observatory designs by EOS date to 1988, but the advent of personal computers enabled EOS Space Systems to engage with the challenge of fully automated observatories in 1995, where five Satellite Laser Ranging Observatories needed to be remote controlled and largely autonomous. Whilst successful, the resulting code base was so complex and tightly coupled as to be contract specific, and could not be further developed. It had become "geriatric", and over one million lines of C++ code was archived.

Applying the Lessons

A new approach to such design was then adopted, placing a high value on loosely coupled functional modules in a multi tiered architecture with generic policy levels. Modules were designed based on whether they performed functions of:

- Network Management
- Site (Observatory) Generic Management e.g. weather, health, external demands, data export
- Observatory Specific Function Management e.g. instrument management, operational sequencing
- Hardware Interface Management

Reaping the Benefits

Based on this hierarchy, the first benefits accrued from the bottom level. In all current EOS observatories, the hardware interfaces are managed by dedicated client-server combinations, and the specific hardware requires a server application which provides a generic I/O interface. In this way, for example, a camera is a camera: it has triggers, an expose period, possibly a gain control, and it sends out images made of pixels. To extend the camera example, images may have noise and may require filtering, or may need an area of interest processed. What is not important any longer is whether the camera is a CCD, EMCCD, sCMOS, APD array or other variety. The server interface to any client application is based on an API, and with tools such as Qt for C++, new clients can be made quickly by modifying an existing client. EOS Space Systems now creates new instrument control interfaces in as little as one day.

The next level is more complex, because it deals with the question of "what does this observatory do?" The approach here is to create an architecture for control which allows the observatory to do many complex tasks in dedicated server programs, with the proviso that the data flow from these servers is of controlled bandwidth, with dense data being processed within the servers to ensure that bandwidth requirements are limited to a fraction of LAN capacity. Now it becomes possible to create clients for remote interface to these servers within the station. By respecting the local bandwidth, all dense data processing occurs before LAN transfer is attempted. The observatory is free now to deal with many server programs on dedicated PCs, using low bandwidth clients elsewhere in the observatory.

System Capability

The range of possible observatory functions now becomes large. Imaging, epoch based autoguiding, laser control, laser return management and data filtering all can be achieved by configuring the site in a suitable way, and by grouping client interfaces on PC desktops to represent desired controls.

Finally, the issue of wide area networking arises. What if the observatory or observatories must be managed from an international base? Once again, the principle of bandwidth policy is used to design the servers and clients for minimal real time bandwidth. It is the principle adopted by games such as HALO and COD, and works well for observatory networks. The Falcon network appears to respect this principle using iLABS and MaximDL.

The key for EOSSS is to respect the needs of real time response at a transactional level. Where data sets are necessarily large and not accessible in real time, a server will be designed to generate a partially processed dataset in real time, which has less information but which is much smaller and contains only essential information for the real time control aspects.

Taking the previous example of images, real time response may be needed if, for example:

- The image is not moving➔ check telescope status and schedule status for errors
- The object of interest is faint and flashing ➔ manually override the autoguide acquisition algorithm
- The star background at V_m18 is obscuring any static blob with streaks ➔engage a temporal filter

What is *not* necessary in the example above is to analyse the object of interest for brightness periodicity in real time, i.e. rotation rate. As a post analysis objective, the uncompressed data can be sent to an FTP site for client upload after the session ends. Therefore, the highly compressed real time image data cannot be used for any photometric purpose, but this is irrelevant by design. The server splits the image stream, saves the large files for later upload, and sends 5kB JPEG or JP2000 versions across the ocean to the logged-in session manager. This is the essence of the network control architecture.

One of our international partners is currently testing the capabilities of remote SSA using the system. Image analysis by mosaic creation in GEO and LEO bands is one area of study, and orbital prediction accuracy is another.

4. Current Developments

Thermal Signature Detection of Orbiting Objects

Having discussed the current capabilities of imagers for detecting and guiding on sunlit objects during a morning or evening terminator phase, the next step is to be able to detect them outside the terminator period each day. Recent analyses by EOS Space Systems have shown that current thermal detection technology is now marginally capable of being adapted to a small aperture, wide field optical assembly capable of detecting space debris from its thermal signature against a dark sky background. Current data suggest that while daylight detection is likely not possible for smaller objects, night phase operation should be feasible. A prototype imager is being designed and built to confirm the theoretical analysis. If successful, the mean productivity of any optical SSA station would be increased from ~180 minutes per day to >600 minutes per day. Using old radar elements as cueing data, the ability to track objects all night creates many new possibilities.

OD/OP Advances

Extending from the ability to detect and “optically” track objects with high accuracy for 10 hours per day per station, recent orbital analysis techniques developed by EOS Space Systems will allow accurate orbital prediction from any object acquired and tracked for 60 seconds. By data mining the historical radar data, the ballistic coefficient errors in the debris catalogue can be corrected. This means that predicted orbits are significantly improved. Also, the tendency for orbital determination algorithms to become unstable and fail to converge can be mitigated by the use of radar elements to “constrain” the solution whilst processing optical centroid based data. The OD becomes more reliable, and the OP becomes more accurate. Refer to 2013 EOSSS publications for details.

It must be acknowledged here that these improvements are valuable but also relative. In absolute terms of orbital prediction accuracy, no short arc determination is precise enough to match the value of a second pass, which effectively lengthens the arc by orders of magnitude. The value of a SSA global network is implicit in this key fact.

This creates five levels of orbital prediction reliability/ accuracy based on technique:

1/ short arc single pass centroid analysis, and frame of reference conversion - usually OD solution fails

2/ enhanced centroid single pass analysis, with ballistic coefficient fixing and radar TLE constraining

3/ laser tracked short arc single pass with BC fixing and radar TLE constraining - useable OD/OP

4/ double pass analysis (longer arc solution) with BC fixing and TLE constraint - gives better OD/OP

5/ 3+ pass analysis (long arc solution), requiring multiple harmonised stations - excellent 48 hour OP

EOS Space Systems sets its strategic research objective at being able to predict conjunction risk 72 hours in advance, with approach confidence interval of <100m. This is regarded as a useful warning envelope for the recommendation of using minimal manoeuvring fuel. Associated research papers are available on request.

Adaptive Optics For Laser Tracking

Assuming a beam director with missile tracking smoothness, coupling of laser energy to a space debris object suffers from the seeing limit of the atmosphere more than by the diffraction limit of the transmit beam. The coupled energy has been experimentally shown to vary in direct proportion to the apparent real-time image offset from the laser boresight caused by Line Of Sight (LOS) seeing variations during the pass.

Even with microradian tracking smoothness, the energy coupled is limited by the 10 microradian seeing wander and beam divergence in the air. The sizes of isokinetic and isoplanatic patches are natural limitations which cannot be ignored for ground based laser operations.

Simple geometry shows that by use of adaptive optics to reduce the beam divergence by four times, the coupled energy will be increased by a factor of sixteen, given suitable tracking smoothness. This is a current initiative at the Space Research Centre at Mount Stromlo, where a laser guide star and wavefront sensor are being developed to enable deformable mirror correction of LOS wavefronts at ~2kHz rates.

The sampling and correction speed of 2kHz is determined by the crossing times of isoplanatic and isokinetic patches of the air column in the line of sight. A wavefront sensor sample must be converted into an antiphase laser pulse within the same isoplanatic and isokinetic patch to be effective. The isoplanatic patch is typically the smaller at ~3 arc seconds (15 microradian) wide for a low altitude observatory. At 3600 arc seconds per second tracking speed, a 3 arc second wide patch is crossed in less than 1msec, so the adaptive optics system latency must be <1msec. In conjunction with the Australian National University’s Adaptive Optics Centre of Excellence, this adaptive optics development represents stage one of a multi purpose AO capability.

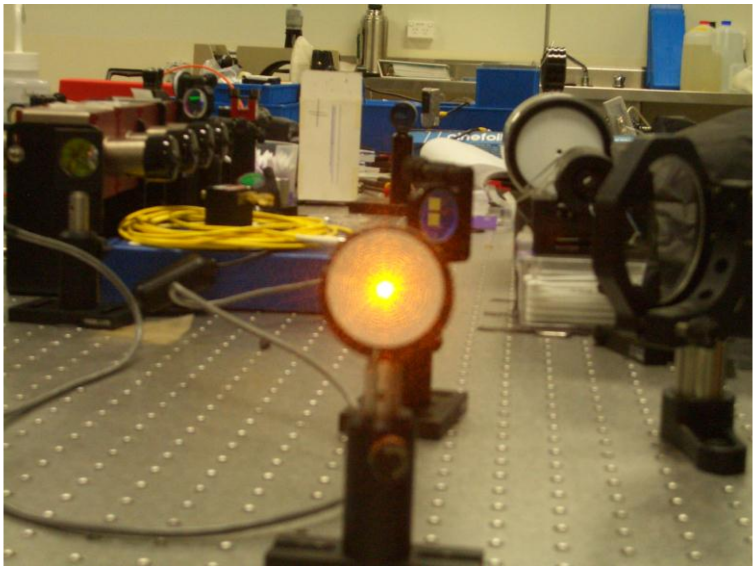

Fig 5: Bench model guide star laser testing in EOS adaptive optics system

Adaptive Optics for CW Laser Pressure: HAMR Object Orbital Modification

Once the high speed AO Demonstrator system is tested on the sky, the next obvious step will be to couple high powered CW laser light to low density debris objects. Analysis by EOS Space Systems shows that the coupled energy needed to alter an orbit is achievable given favourable circumstances. Even a slight retardation and change in eccentricity can shorten an orbital lifetime to a few months, and this research complements other techniques being studied for the clean up of space. Associated papers from EOS Space Systems are available on request.

5. Conclusion

THE SSA observatory capability of the EOS Space Systems' Space Research Centre is maturing steadily after several rounds of prototype development. New research and product development continues to enable SSA needs of the future to be met. As of 2013, the facility is available for remote control by international users, to meet planned and exigent needs wherever the capability of the observatory allows. For passive imaging investigations, laser tracking, orbital element creation, or debris cataloguing, the facility is ready now. If networked suitably, the radar based catalogues could now be supported and enhanced by optical data for highest quality conjunction analysis. The next step will be NEO debris orbital influence, to assist with the urgent need to clean up this essential orbital band for safe use once again.