Angles and Range: Initial Orbital Determination with the Air Force Space Surveillance Telescope (AFSST)

John T. McGraw, Mark R. Ackermann,
Peter C. Zimmer, M. Suzanne Taylor
The University of New Mexico

Jeffrey R. Pier
US Naval Observatory, Flagstaff

Maj. Brian Smith
AFRL/RDSA

and the UNM Measurement Astrophysics (MAP) Research Group

ABSTRACT

The institution of a robust, comprehensive program of Space Situational Awareness (SSA) necessarily includes observations by ground-based optical and infrared (OIR) telescopes. The Air Force Space Surveillance Telescope (AFSST) has been proposed as a system of telescopes designed to address the ground-based component of comprehensive SSA. A hallmark of our definition of AFSST is that it be composed of inexpensive, replicable telescopes programmed to accomplish multiple surveillance programs, but designed to achieve the difficult design-driving task of accomplishing an uncued search for small objects in Low Earth Orbit (LEO).

We discuss the configuration of AFSST and describe one technique by which AFSST simultaneously acquires angle and range data for accurate real-time determination of LEO orbital elements, even upon first detection of the object.

1.0 ORBITAL DATA – THE BASIS OF SSA

Space Situational Awareness (SSA) is a national priority that addresses several agendas, including a significant role in stabilizing the world. A known excellent SSA system deters attempts to use the "high ground of space" for nefarious purposes. If sufficiently robust, and SSA system has the necessary capability of providing information that allows correct and unbiased census and assessment of the content and configuration changes amongst objects contained in near-Earth space. Identification, orbital determination and characterization of objects included in a service volume[1] extending beyond geosynchronous orbital range are primary goals of any SSA system.

Because a working and workable SSA system is difficult to implement, multiple systems including a variety of sensor suites will legitimately be required to cover the physical parametric volume embedded in the SSA service volume. The fundamental measurement parameter space includes range, brightness, orbital angular rate, and the object's spectral energy distribution (SED). Changes in these parameters represent cause for enhanced observation as provided by current and future AF assets including radar and optical/infrared (OIR) systems.

---

[1] The *service volume* of an SSA system is defined as the volume of space centered on Earth for which the SSA system can unequivocally detect and track orbiting objects of specified brightness. The *parametric volume* converts the specified brightness to physical parameters including the projected object size, albedo, illumination conditions, spectral energy distribution, etc.

Each sensor suite includes unique attributes – *pros* and *cons* – that determine its range of utility. For example, Low Earth Orbit (LEO) has long been the purview of radar-based search and surveillance systems, principally because radar affords a large field of view and because range is included in the return data for each satellite detection. Radar and optical techniques have been used for monitoring satellites at larger ranges. At large ranges the task of monitoring space gives way to optical systems which do not require isotropically radiated electromagnetic energy to achieve detections. The majority of optical monitoring systems rely upon solar illumination, though active illumination is certainly possible. While optical detection provides good angular resolution and track information, passive systems do not directly provide range information as do radar and LADAR systems.

Here we consider the use of multiple simultaneous optical observations to derive range at the time of discovery for uncued search observations, as well as the utility of these observations to routinely include range in orbital solutions. The acquisition of multiple simultaneous observations of objects is embedded in the architecture of the Air Force Space Surveillance Telescope (AFSST), a distributed system of telescopes previously described in this series.

One goal of AFSST is to derive as much information as possible, especially about newly-discovered objects. In priority order, we require as complete an orbital solution as possible, and we need characterization data. The "Bible of Orbits," Vallado's "Fundamentals of Astrodynamics and Applications" [1] clearly states that the optimal orbital solution is based upon accurate measurements of two angles and a range, and the rate of change of each. In an effort to explore how well this task can be accomplished on initial contact, we've considered techniques by which range, to some useful accuracy, might be measured. We thus consider parallax based upon simultaneous observations by telescopes with well known baselines as range estimates to complement the excellent angle and angular rate information provided by OIR observations.

While experiments with parallax measurements have apparently been attempted, the technique is not in widespread use for optical sensor systems. Problems include obtaining simultaneous measurements from two suitably spaced telescopes, the fast angular rates of the objects, and the limited time when the object's phase angle allows appropriate solar illumination from two sites. In the spirit of carefully examining useful techniques to support SSA in general, we elect to re-examine the utility of parallax measurements in a variety of modifications as a conceptually simple technique for deriving accurate range to orbiting objects. The context for this discussion is our earlier definition of the Air Force Space Surveillance Telescope (AFSST) [2], in fact a *system* of ground-based OIR telescopes specifically defined for SSA, as well as for theater-scale deployment.

We first discuss the concept of parallax and then review the characteristics of AFSST, especially its deployment configuration and the wide field of view optics employed by a set of its surveillance telescopes. Finally examine parallax techniques as used by astronomers and apply modified versions to orbiting object detection and range measurement in an effort to test the utility of OIR range determination techniques.

2.0 PARALLAX – AN ANCIENT ASTRONOMICAL TECHNIQUE FOR GEOMETRIC DISTANCE ESTIMATION

Ancient astronomers understood that by observing an object in the sky from two vantage points that the distance to the object can be derived using relatively straightforward trigonometry [3]. An example of terrestrial parallax is shown in Fig. 1, where we see that the determination of distance is made possible by creating a displacement of the location of the observer. This is the basic distance measurement technique we propose for satellites, with people replaced by telescopes.

For centuries astronomers have used the parallax technique to measure distances to astronomical objects. Hipparchus rather successfully used geometrical parallax in about 130 BCE to estimate the distance from the Earth to the Moon. Because distance is the most difficult astronomical parameter to measure, the technique has been greatly refined, and parallax distances form the fundamental basis for the entire astronomical "distance ladder." Distances to galaxies and quasars are measured using a system of measurement techniques that begins with parallaxes for nearby stars. Fig. 2 illustrates the astronomical *annual parallax* that uses the diameter of Earth's orbit about the sun as the baseline to measure trigonometric distances to stars.

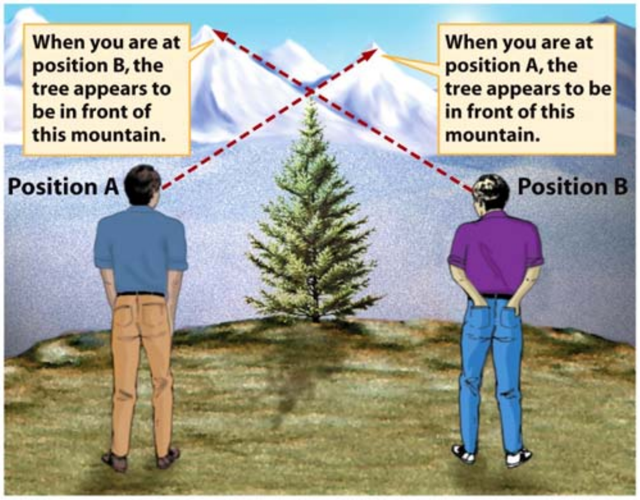

Fig. 1. Parallax results from viewing a nearby object relative to much more distant objects from multiple positions. These people can calculate the distance to the tree from trigonometry. The people and the tree form a triangle with the length of the base equal to the distance between the two gentlemen – a distance that can be easily and accurately measured. Each person measures an angular displacement of the tree relative to the distant background. Equivalently, for a short baseline the men can measure the angle between the base (the line between them) and the tree, allowing the altitude of the triangle – the perpendicular distance from the base to the tree – to be calculated [3].

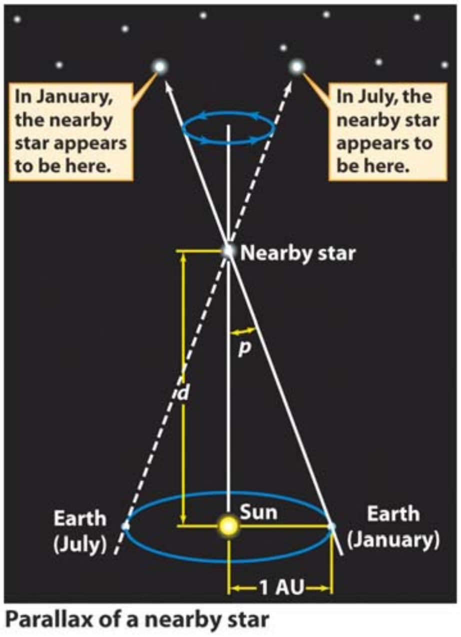

Fig. 2. The astronomical annual parallax to a nearby star is defined as the half-angle of the vertex of a triangle with the orbit of the Earth about the sun as the base. The mean distance of the Earth from the sun is one Astronomical Unit (AU: 149,597,870.69km ± 0.03km). The annual parallax is thus defined as $p = 1\text{AU}/d$, where d, the distance to the star, is canonically measured in AU [3]. Similarly, the distance to an Earth-orbiting satellite can be accurately measured if it can be simultaneously observed by two telescopes separated by an accurately known distance, or by modified versions of this basic technique.

Astronomical parallaxes, that is, the distances principally to stars and solar system objects, are routinely measured using ground- and space-based telescopes. The most common technique for distance determination used by astronomers is to employ annual parallax – the parallax measured from the Earth at widely separated points on the Earth's orbit about the sun. Repeated observations of a suspected nearby star are made, typically with the same telescope, during the course of an annual observing season (approximately six months). The relative positions of stars in the field of view of the telescope are carefully measured and the angular motion of the nearby star relative to background stars is interpreted as a parallax measurement leading to a distance estimate.

The issue is that even the nearest stars are so distant that the largest stellar parallaxes are exceedingly small angles. Astronomers have become proficient at using telescopes to measure small angles with small uncertainties. As an example, Table 1 lists the 14 stars with annual parallax greater that 300 milliarcseconds (mas) from the Gliese Catalog of Nearby Stars [4] [5]. For translation purposes, 300mas = 0.3arcsecond = 0.3arcsec x 4.85microradian/arcsec ~ 1.5 microradian. And this is a "large" parallax by astronomical standards. We make this comparison simply to reinforce the idea that small angles can be measured precisely and that these parallaxes yield accurate distances. From Table 1, the nearest star, Proxima Centauri, has a parallax of 0.7718arcsec and is at a distance of 1.296 parsecs = 267,252 AU, or ~ 4 x 10^{13}km. Scaling to a LEO object at 400km measured on a 100m baseline yielding a parallax of 25.8arcsec, an instantaneous satellite parallax is ~ 33 times larger, hence much easier to measure.

Table 1. The 14 Closest Stars from the Gliese "Catalog of Nearby Stars"

Giclas Catalog Number	Right Ascension (Degrees)	Declination (Degrees)	Apparent Magnitude (V)	Spectral Type	Trigonometric Parallax (mas)	Parallax Uncertainty (mas)	Common Name
Gl 447	176.9284	0.8221	11.12	dM4.5	301.1	1.9	
Gl 144	53.2449	-9.4589	3.73	K2 V	305.6	2.6	ε Eridani
Gl 905	355.4763	44.1974	12.29	dM6 e	315.6	1.6	
Gl 729	282.4487	-23.8335	10.46	dM4.5e	341.1	8.1	
Gl 244B	101.2962	-16.6999	8.44	DA2	380.4	2.9	
Gl 244A	101.2962	-16.6999	-1.43	A1 V	380.4	2.9	Sirius
Gl 65B	24.7072	-17.9581	12.70	dM5.5e	380.7	4.3	
Gl 65A	24.7072	-17.9581	12.57	dM5.5e	380.7	4.3	
Gl 411	165.8457	36.0355	7.48	M2 Ve	397.3	1.8	HD 95735
Gl 406	164.1754	7.0526	13.45	M6	418.3	2.5	
Gl 699	269.4644	4.5509	9.55	M5 V	545.3	1.0	
Gl 559B	220.0028	-60.8448	1.34	K0 V	749	4.7	α Centauri B
Gl 559A	220.0028	-60.8448	0.01	G2 V	749	4.7	α Centauri A
Gl 551	217.5433	-62.6906	11.05	dM5 e	771.8	4.1	Proxima Cen

Given the astronomical case, we can assess the problem of satellite parallax measurements. Fig. 3 shows the terrestrial parallax measured with a 100m baseline as a function of range for satellites displayed both in units of radians and arcseconds (for the astronomers). We note that the parallax for objects in LEO are one arcsec or greater – easy to measure by comparison to Table 1. Even at GEO, where measurements can be integrated to achieve excellent signal-to-noise (S/N), the parallax exceeds 0.25arcsec. Satellite parallaxes are therefore "easy" to measure – provided that our telescopes can see them, and that the image S/N is significant! Certainly parallax determination can be a significant adjunct to orbital data determination, especially for ranges beyond which radar and LADAR become ineffective. This includes the transitional volume between LEO and GEO in which transfer orbits occur.

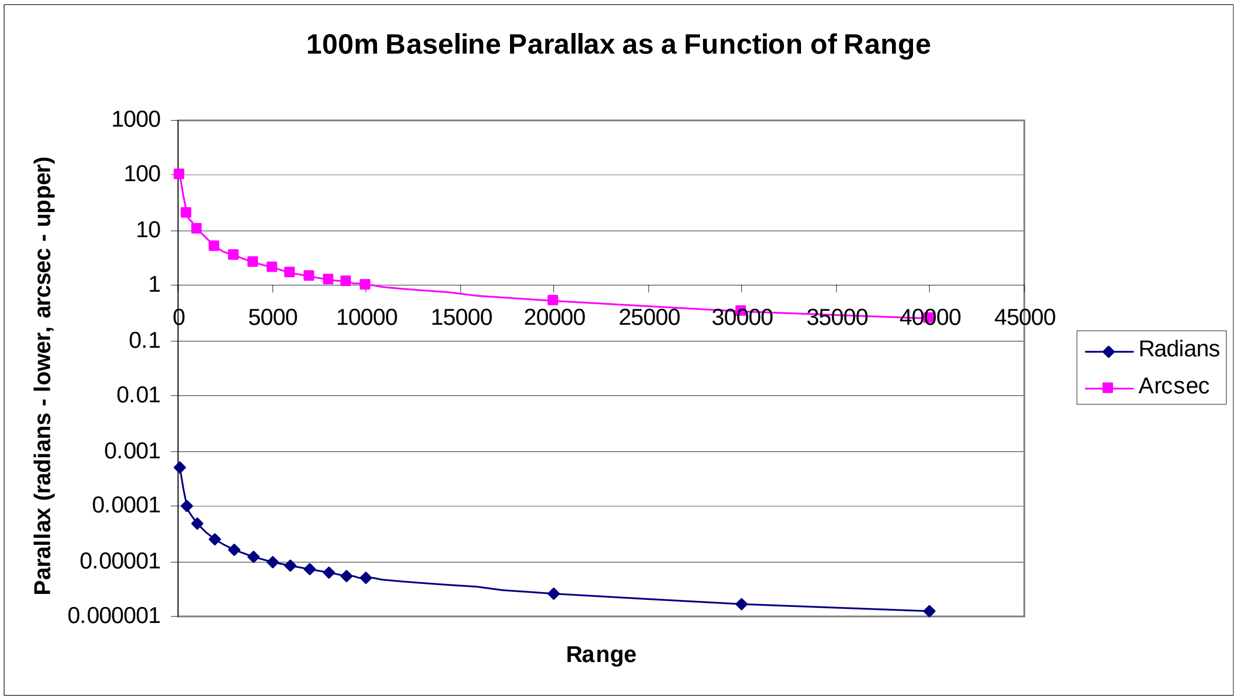

Fig. 3. Parallax as a function of range for Earth-orbiting objects measured on a 100m baseline. The upper curve shows parallax in units of arcseconds and the lower curve shows the same parallax in units of radians. Astronomers' long-term expertise with small angle measurement can support satellite range estimation.

A principal issue for using "single field" astrometry is that parallax measurements are made relative to other stars in the field of view. The critical issue is that precise positions of reference stars must be known at the time the parallax observations are made. Secondly, the field of reference stars are virtually certainly more distant than the nearby "program star" for which a parallax is sought, but they are not "infinitely" distant. This requires that a statistical correction be made for the distribution of distances of the reference stars. This correction depends upon the type of stars, that is, their intrinsic luminosities, and thus their distance as inferred from their apparent magnitudes. The US Naval Observatory has long conducted the mission of providing the world with catalogs of positional standard stars and their motions, originally for navigational purposes, but now for other applications, such as space surveillance, and the astronomical investigation of our Galaxy of stars. A product of the USNO stellar catalog generation has always included parallax measurements leading to distances to stars. Current USNO positional catalogs include USNO-A2.0 [6], USNO-B1.0 [7], UCAC-2 [8] and the merged set of catalogs, NOMAD [9], including data from HIPPARCOS [10, 11], Tycho-2 [12], UCAC-2 [8], USNO-B1.0 [7] supplemented with data from 2MASS [13].

The final intrinsic issue is whether terrestrial parallax measurements have inherent accuracy sufficient to the task of deriving useful range to orbiting objects. Taking $d = 1/p$, the formal uncertainty in the distance determination is $\Delta d = -p^{-2} \Delta p$. While astronomers have estimated Δp, the uncertainty of a parallax measurement, in numerous ways [14, 15, 16], because we are looking for feasibility, we simply solve for Δp given the experiment we intend to try. For a zenith range d = 400km measured on an E-W 100m baseline centered on the meridian, the classical parallax $p = 50\text{m}/400\text{km} = 1.25 \times 10^{-4}$ radian = 25.8 arcsec. For a range uncertainty of 1m, $\Delta p = 0.003$ arcsec, or 3mas. This demonstrates that while a 400km satellite presents a "large" parallax, the *precision* of the range measurement depends upon the *precision* of the parallax measurement. Even large values of terrestrial parallax must be measured with high precision to precisely determine range. While not out of the question, a few milliarcsecond parallax precision cannot be routinely measured by classical techniques for single satellite apparitions.

The actual limiting factor in measurement precision is the S/N of the satellite detection. In practice a parallax precision of less than 1arcsec is rather easily achieved, even for short exposures with a sky survey pixel resolution of ~ 1 arcsec, because the astrometric precision δp principally depends upon the S/N of the individual measurements.

For individual images with S/N = 10, 2arcsec PSF sampled with 1arcsec pixels, $\delta p \sim (S/N)^{-1}$ yielding 0.2arcsec per image measurement and 0.28arcsec for the differential parallax measurement, resulting in range resolution of about 2km at 400km, or 0.5% of the range. Sub-arcsec parallax resolution, yielding distinctly useful range estimates, is possible for sufficiently high S/N. While not as precise a range that can be obtained by radar, it is a useful value, especially for a discovery observation, and can be used to refine orbital parameter estimates. Additionally, this measurement is obtained "for free" as the result of appropriate configuration of survey telescopes.

We have considered an example of a LEO object in a 400km orbit. Parallax yields a useful range estimate, though not as precise as a radar or LADAR range. Optically derived distances become more important as range increases because satellites under-fill a radar beam leading to the well-known $1/d^4$ detected power losses which rapidly become significant as range, d, increases.

Additionally, optically derived angles are also precise at the 1arcsec level and, as always for images with sufficient S/N, are approximately constant with range out to and beyond GEO. Optical and radar observations have been compared as a basis for updating LEO orbital parameters and OIR measurements are found to be usefully precise and accurate [17]. We agree with this assessment and propose that considering the applicability of range derived from optical observations yields even more useful data for orbit determination from LEO to GEO.

It is clear that optical orbital determination techniques, and parallax techniques in particular, can produce useful, and possibly valuable, range information and the use of parallax to supplement the catalog of orbital parameters should be investigated. Certainly, range data beyond LEO, beyond the range where radar is generally applicable, is useful for orbital determinations and is measurable by OIR techniques.

3.0 THE AIR FORCE SPACE SURVEILLANCE TELESCOPE: SYSTEM CONTEXT

The definition of the system of telescopes that constitute our proposed Air Force Space Surveillance Telescope (AFSST) has been chronicled in these proceedings [18, 2, 19, 20, 21, 22). The driving task for AFSST is the uncued discovery, orbital determination and characterization of microsats in LEO. This task was selected firstly because it is a significant mission that needs to be addressed, and secondly because the ability to accomplish this task makes surveillance of space at higher altitudes and for different purposes relatively "easy." Virtually all other OIR surveillance tasks are subsumed by the ability to perform the LEO discovery task.

- AFSST drivers and concepts include:
    - Design the least expensive, most efficient individual telescopes capable of accomplishing the SSA mission.
        - As small as possible for the mission
        - Replicable and inexpensive
        - Field operable and serviceable
        - Deployable
        - Normally passive, but capable of use with active illumination
    - Design of an extremely high throughput wide field-of-view optical system <u>optimized for detection</u>, not high angular resolution.
    - Design of a mosaic of detectors that can be electronically read out under computer control in unique ways:
        - "Freeze" a fast-moving satellite
        - Derive approximate altitude information from a single pass
        - Estimate satellite color from multi-bandpass detections
    - Telescopes are deployed worldwide in about 5-10 groups of approximately 10 telescopes each:
        - Each group of ~ 10 telescopes ensures operational redundancy and cyclical service
        - Groups of telescopes are separated in longitude to provide continuous nighttime coverage
        - Groups located at similar longitude will be at different latitudes and in different weather systems to optimize on-sky surveillance
        - Groups will located to survey "high value" regions of space – north/south poles, equator, and others

    - Real-time coordinated operation of each group allows optimal sky surveillance plus triangulated altitude of detected satellites
    - Groups will communicate in real-time and some telescopes at each site will observe satellites <u>predicted</u> to appear from previous detections, including immediately prior discoveries
- Additional telescopes can be rapidly deployed for theater surveillance
    - Two telescopes designed to fit a standard deployable container
    - Field group easily removed, relocated or destroyed in place
    - Immediately integrate into AFSST system
- AFSST data system operates as an integrated, real-time "predictor-corrector" structure
    - Detections used to derive position, motion, altitude and color of satellites
    - New detections immediately included in data system
    - "Hand-offs" among the groups will allow continuous nighttime observation of satellites predicted to be visible by the data system from observations obtained by previous groups
    - Non-detection of predicted satellite passage provides useful information for the data system
    - Non-detection, orbital change, color change are possible "trigger mechanisms" for human notification and decision-making
- AFSST can be designed, tested and produced in a structured, stepwise low-risk manner with prototypes easily built, deployed and tested

A highly conceptual notional cartoon configuration for AFSST is shown in Fig. 4, and a strawman deployment map is shown in Fig. 5, both figures stressing the fact that AFSST is envisioned as a *system* of specially-designed telescopes.

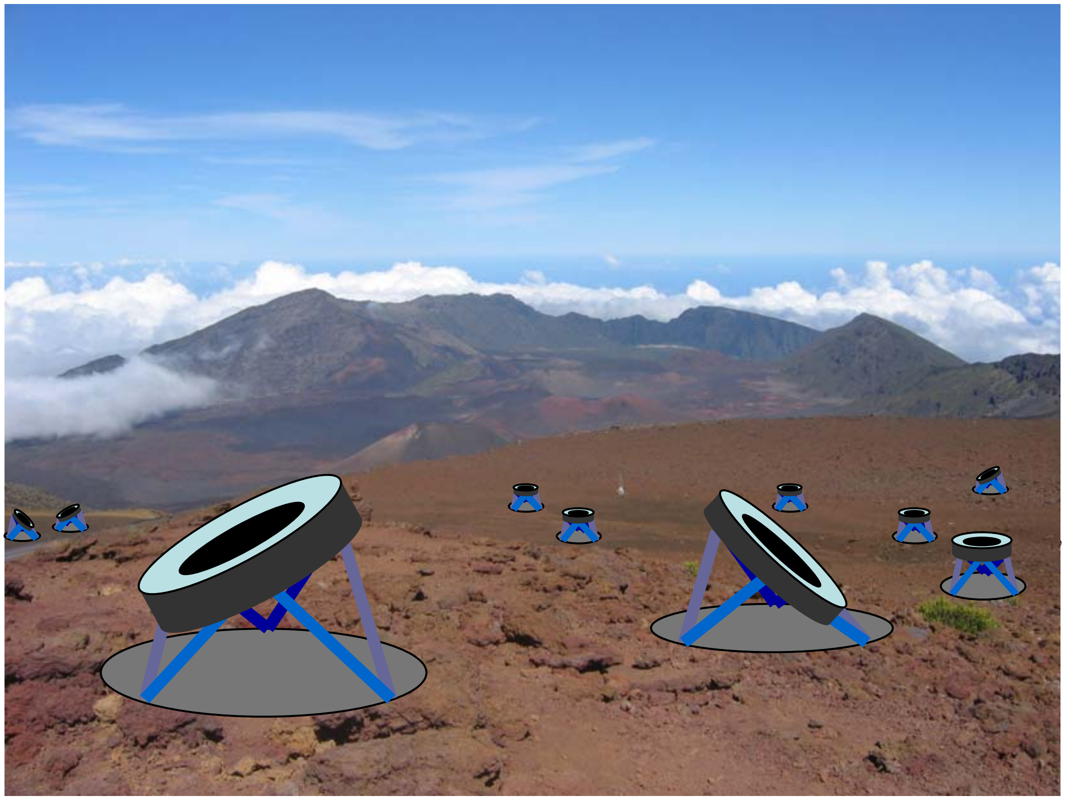

Fig. 4. Notional concept of one AFSST group showing 10 hexapod-mounted wide-field surveillance telescopes. The baselines among the surveillance telescopes allow range estimates via terrestrial parallax measurements for detected satellites that are included in their overlapping fields of view.

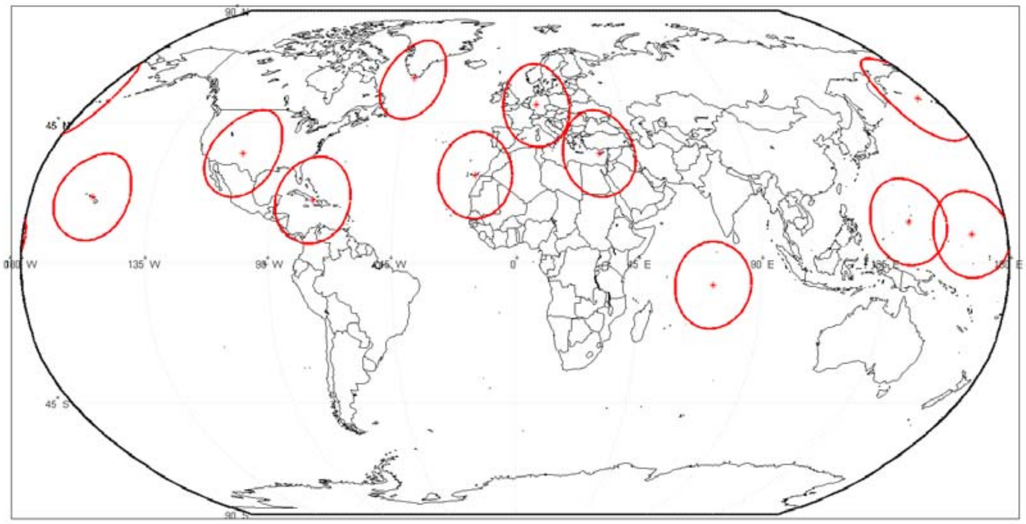

Fig. 5. Conceptual deployment of AFSST groups Distances between groups can also be used in some cases for quasi-diurnal parallactic range measurements. The red circles represent the horizon-to-horizon surveillance limit for 300km LEO orbits.

4.0 OIR SATELLITE RANGE ESTIMATES FROM PARALLAX MEASUREMENTS

The primary difficulty in applying parallax measurement for range determination is that the angular rates of LEO satellites are large, resulting in short integration times and commensurately low S/N per detection. Previously we've discussed designs for wide field of view telescopes that address the AFSST mission, and a 5° FOV is achievable and will provide image quality and detector pixel match to survey in excess of 5000 square degrees per hour with pixel resolution of $\leq$ 1arcsec. This pixel resolution is sufficient to derive sub-arcsec parallax measurements directly from overlapping fields-of view. Fig. 6 shows the apparent angular velocity as a function of altitude for LEO satellites, from which we see that for a 400km orbit the angular rate is approximately 1.1deg/sec. The maximum integration time for the satellite to traverse a 5° FOV is thus 4.5s. The actual integration time in the FOV will depend upon the actual track of the satellite across the focal plane detector mosaic, usually shorter than 4.5s, and the actual zenith angle of observation, which somewhat lengthens the integration time because of the projection effect.

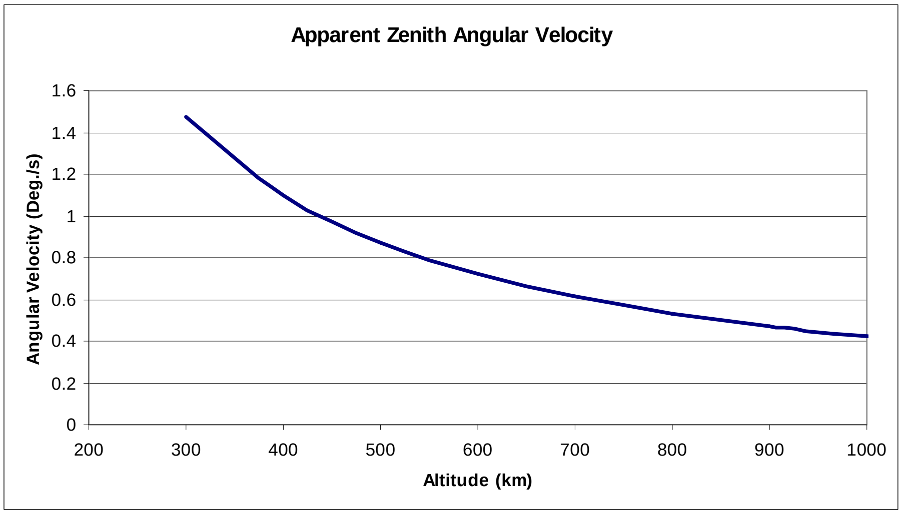

Fig. 6. The zenith apparent angular velocity for LEO satellites.

The real issue for basic parallax determination is that the satellite must appear in the focal plane of at least two telescopes simultaneously. We thus evaluate the *overlap function* for two telescopes as a function of range. The overlap function is the fraction of the fields of view (FOV) of the two telescopes that coincide at a range R. The formalism for this problem is identical to that for evaluating the overlap of a bistatic lidar laser and the FOV of its receiver. We therefore adopt the formalism of Measures [23] depicted in Fig. 7.

This geometry results in three overlap cases shown in Fig. 8. At range R the projected distance, d, between FOVs of the reference telescope with projected field radius r_T and the second telescope with projected field radius w is greater than $(r_T + w)$ and the FOVs don't overlap at all. The overlap function has value 0 for Case a. Case b represents the partial overlap of the two fields, and Case c shows the second telescope field completed within the field of the reference telescope and the overlap function has value 1 as long as this condition is maintained. In this case the useful parallax search volume is determined by the smaller aperture. In practice we anticipate telescopes of the same aperture, in which case $r_T = w$ and the FOVs are of the same projected size at and R and can be caused to overlap completely at R by adjusting δ. Note that this technique selects a volume of space because the overlap will again diminish with R as the optical axes diverge.

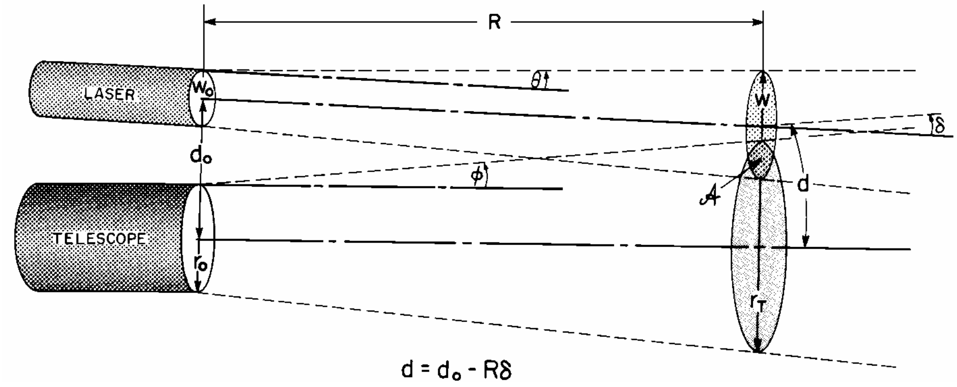

Fig. 7. Geometry of a biaxial lidar from Measures [23]. Modified for the two telescope surveillance case, the laser is simply another telescope, and the FOVs overlap in area A at range R, depending upon the radii of the initial apertures (r_0 and w_0) and their initial spacing d_0, the angle between the optical axes, δ, and the divergence of the FOVs (ø and θ). The separation of the centers of the FOVs at range R is d.

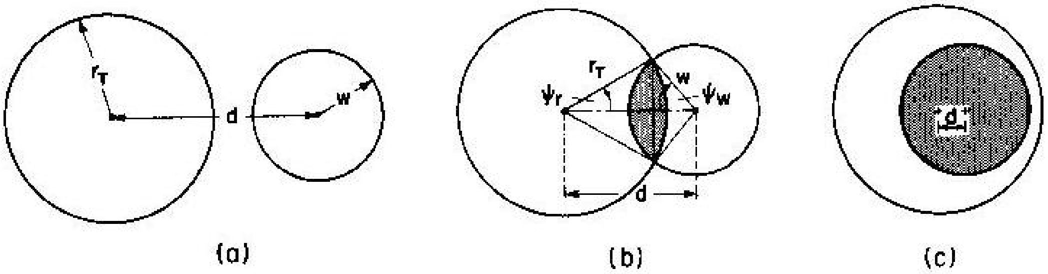

Fig. 8. The three cases of overlap for the FOVs of two telescopes adopted from Measures [23]. Case a represents an overlap function of 0 – the fields do not overlap at all. Case b shows partial overlap, whereas Case c shows an overlap of 1 for which the second telescope FOV is smaller than and totally contained in the FOV of the reference telescope. The shaded areas yield potential parallax measurements.

Note that the volume of space useful for determination of parallaxes can be controlled by tailoring the overlap volume by combining telescopes of different aperture and by adjusting the angle between their optical axes.

Parallax measurement requires evaluating the image of a satellite at the same time in the FOVs of two telescopes. Maintaining "absolute time" between telescopes and amongst the AFSST system can be achieved using timing information provided by the GPS system.

The second issue is to determine a center of light for a satellite, which in the most common observing mode, sidereal tracking, will appear as a streak amongst a field of stars. An example is shown in Fig. 9.

Fig. 9. A satellite streak amongst a field of stars acquired in staring mode (sidereal track) mode of observing. If observed by two telescopes this streak will yield a classical terrestrial parallax determination if position along the streak can be referenced in time.

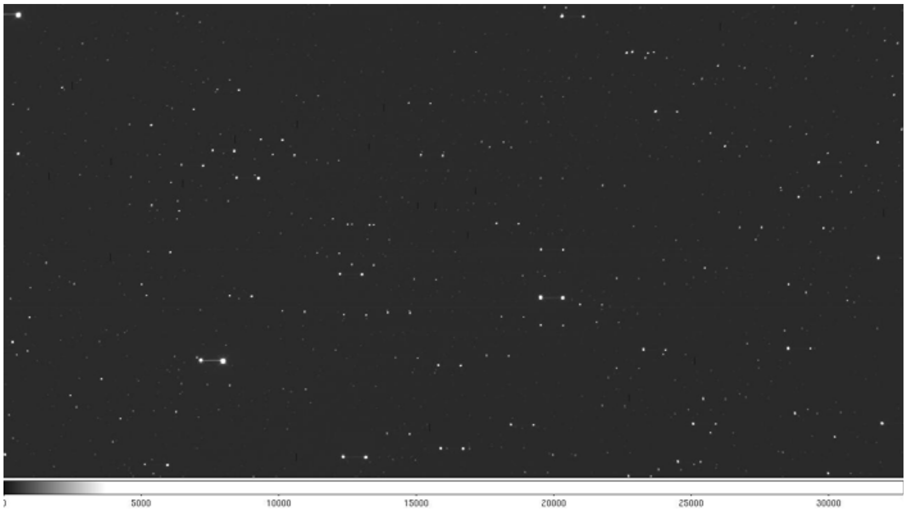

Fig. 10. A modulated CCD image can be used to embed accurate time hacks into image data. Multiple displacements with unequal intervals allow determination of the direction of motion of a satellite leaving a track in the image. The fields of view of multiple telescopes can be angularly registered by the star images, and registered in time by the displacements. These data are sufficient to derive a terrestrial parallax and a range estimate.

One technique to reference a streak image in time is to modulate the detector, in our case a CCD, such that "time hacks" are precisely embedded in the image accurately at specific times. This can occur by modulating the CCD image using its readout electronics to displace the integrating image at appropriate time intervals – typically of the order one second of time. In our example this will provide approximately four time hacks for a satellite transiting a 5° FOV. An example of field displacement is show on Fig. 10, where the time of the displacement is accurately known. Multiple displacements can occur on a single image. Each displacement results, in general, in a lateral displacement of the satellite track.

Our discussion has centered on LEO objects, principally because the mission driver for AFSST involves an uncued search and immediate orbital parameter estimation for LEO objects. Our point, once again, is that the LEO ranges themselves provide the most stringent limitations on the application of AFSST, including for range estimates. The most obvious issue resulting from their proximity to Earth is that LEO objects are usually observed at sunset and sunrise.

During the remainder of the night AFSST can with better efficiency apply its detection, angle and rate measurements, and especially the parallax techniques, to objects in higher orbits, including those in transfer orbits for which the range will be rapidly changing.

There are multiple scenarios for measuring the parallax of an orbiting object which we are still exploring.

Given that any range estimates are useful for rapidly and better constraining the orbital determination of objects, especially as they are discovered [1], we suggest that OIR techniques based upon parallax can make significant contributions to our knowledge base of orbital space, and that these techniques should continue to be investigated.

5.0 SUMMARY

Orbiting object range estimates derived from classical parallax measurements are feasible and valuable. From the astronomical perspective, the parallaxes of satellites are large, and therefore easily measured. The precision of measurement determines the accuracy of the distance measurement. The ultimate accuracy is a complicated function of the satellite range and orbit, as well as the optics of the telescopes. Range estimates made at discovery are important for initial orbital parameter estimation and parallax measurements can provide parallax-derived range estimates for these objects. The satellite S/N is, in general, greater for larger range because the integration time canonically increases with range, thus allowing accurate measurement for objects beyond the usual range of radar. Parallax measurements of satellites in transfer orbits might be especially useful.

Innovative techniques for parallax determination can be brought to bear, allowing this form of range measurement to contribute to a comprehensive space surveillance campaign and provide a complement to a comprehensive SSA plan.

6.0 REFERENCES

[1] Vallado, D. A. 2001, *Fundamentals of Astrodynamics and Applications*, (Kluwer: Dordrecht).

[2] McGraw, John T., Ackermann, Mark R., Martin, Jeffrey B., Zimmer, Peter C. 2003, *The Air Force Space Surveillance Telescope*, Proceedings of the 2003 AMOS Technical Conference, also published as Report No.: **SAND2003-3226C,** Sandia National Laboratories, Albuquerque, NM (USA), September 2003.

[3] Freedman, R. A. and Kaufmann III, W. J. 2008, *Universe*, Eighth Edition (Freeman: New York).

[4] Gliese, W. and Jahrheiss, H. 1991, *Preliminary Version of the Third Catalogue of Nearby Stars*, Astronomisches Rechen-Institut, Heidelberg.

[5] http://heasarc.gsfc.nasa.gov/W3Browse/star-catalog/cns3.html

[6] http://tdc-www.harvard.edu/software/catalogs/ua2.html

[7] Monet, D. G., Levine, S. E., Canzian, B. and 26 other authors 2003, Astron. J. **125**, 984. "The USNO-B Catalog."

[8] Zacharias, N., Urban, S. E., Zacharias, M. I., Wycoff, G. L., Hall, D. M., Monet, D. G. and Rafferty, T. J. 2004, Astron. J. **127**, 3043. "The Second US Naval Observatory CCD Astrograph Catalog (UCAC2)."

[9] Zacharias, N., Monet, D. G., Levine, S. E., Urban, S. E., Gaume, R., Wycoff, G. L. 2004 BAAS, **36,** 1418. "The Naval Observatory Merged Astrometric Dataset (NOMAD)."

[10] Turon et al. 1992, ESA SP-1136.

[11] The HIPPARCOS and Tycho Catalogues 1997, ESA SP-1200.

[12] Høg *et al*. 2000, Astron. Astrophys. **355**, L27. "The Tycho-2 Catalogue of the 2.5 Million Brightest Stars."

[13] http://www.ipac.caltech.edu/2mass/releases/allsky/

[14] Strand, K. Aa. 1963, "Trigonometric Parallaxes" in *Basic Astronomical Data* (University of Chicago Press: Chicago), ed. Strand, K. Aa., p. 55.

[15] Kovalevsky, J. and Seidelmann, P. K. 2004, *Fundamentals of Astrometry*, (Cambridge University Press: Cambridge).

[16] Harris, H. C., Canzian, B., Dahn, C. C., Guetter, H. H., Henden, A. A., Levine, S. E., Luginbuhl, C. B., Monet, A. K. B., Monet, D. G., Munn, J. R., Pier, J. R., Stone, R. C., Tilleman, T., Vrba, F. J. and Walker, R. L. 2005, "Progress in Parallaxes at USNO" in ASP Conf. Ser. 338, (Astron. Soc. of the Pacific: San Francisco), eds. Seidelmann, P. K. and Monet, A. K. B., p.122.

[17] Alfriend, K. T., Sabol, C, and Luu, K. K. 2004, 2004 AMOS Conference Proceedings, Orbit Update Comparison Using Optical and Radar Systems."

[18] Ackermann, Mark R., McGraw, John T., Martin, Jeffrey B., Zimmer, Peter C. 2003, *Blind Search for Micro Satellites in LEO: Optical Signatures and Search Strategies*, Proceedings of the 2003 AMOS Technical Conference, also published as Report No.: **SAND2003-3225C,** Sandia National Laboratories, Albuquerque, NM (USA), September 2003.

[19] Ackermann, M. R., McGraw, J. T., Zimmer, P. C., Golden, E. 2005, *Optical Design Trade Space for the Air Force Space Surveillance Telescope*, Proceedings of the 2005 AMOS Technical Conference, pp. 333 - 362.

[20] Ackermann, M. R., McGraw, J. T. and Zimmer, P. C. 2006, *Are Curved Focal Planes Necessary for Wide-Field Survey Telescopes?*, Proc. Soc. Photo-opt. Inst. Eng. **6267**, 626740.

[21] Ackermann, M. R. and McGraw, J. T. 2007, *Large-Aperture, Three-Mirror Telescopes for Near-Earth Space Surveillance: A Look from the Outside In,* Proceedings of the 2007 AMOS Technical Conference, p. E6.

[22] McGraw, J. T. and Ackermann, M. R. 2007, *A 1.2-m Deployable, Transportable Space Surveillance Telescope Designed to Meet AF Space Situational Awareness Needs*, Proceedings of the 2007 AMOS Technical Conference, p. E4.

[23] Measures, R. M. 1984, *Laser Remote Sensing: Fundamentals and Applications*, (Wiley: New York).