Historical Trends in Ground-Based Optical Space Surveillance System Design

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ABSTRACT

An historical overview of ground-based optical space surveillance systems is provided, with specific emphasis on gathering metrics to analyze design trends. Systems are categorized by their orbit determination or space object identification purposes, the orbital regime of their targets, and their industry segment. The influence that commercial off-the-shelf equipment has had on capabilities is also explored, particularly regarding amateur systems. The data clearly show an early emphasis on low Earth orbit (LEO) observations, followed by renewed interest in geosynchronous objects (GEO). Overall, LEO systems show increasing aperture over time, with both LEO and GEO systems generally having decreasing field of view.

1. INTRODUCTION

In the spirit of the 50th anniversary of the launch of the first man-made satellite, an historical overview of ground-based optical space surveillance systems is provided. Specific emphasis is given on gathering metrics to analyze design trends. The subject of space surveillance spans the history of spaceflight: from the early tracking cameras at missile ranges, the first observations of Sputnik, to the evolution towards highly capable commercial off-the-shelf (COTS) systems, and much in between. Whereas previous reviews in the literature have been limited in scope to specific time periods, operational programs, countries, etc., a broad overview of a wide range of sources is presented.

This review is focused on systems whose primary design purpose can be classified as Space Object Identification (SOI) or Orbit Determination (OD). SOI systems are those that capture images or data to determine information about the satellite itself, such as attitude, features, and material composition. OD systems are those that produce estimates of the satellite position, usually in the form of orbital elements or a time history of tracking angles. Obviously some systems would be capable of performing both tasks to varying degrees, and therefore systems are classified based on their apparent primary design purpose.

Systems are also categorized based on the orbital regime in which their targets reside, which has been simplified in this study to either Low Earth Orbit (LEO) or Geosynchronous Earth Orbit (GEO). The systems are further classified depending on the industry segment (government/commercial or academic), and whether the program is foreign or domestic. In addition to gathering metrics on systems designed solely for man-made satellite observations, it is interesting to find examples of other systems being similarly used. Examples include large astronomical telescopes being used for GEO debris surveys and anomaly resolution for deep-space probes. Another interesting development is the increase in number and capability of COTS systems, some of which are specifically marketed to consumers as satellite trackers. The review is restricted to systems that use natural sunlight to illuminate targets for two reasons: these systems have a longer history, and a major motivation was analyzing trends in amateur involvement. Lastly, all references were obtained from publicly available, unclassified sources.

After describing the results of the literature review and presenting further information on various systems, we gather specific metrics on the optical design. Aperture and field of view (FOV) are plotted with time to ascertain trends in ground system design. Aperture is a useful metric because it gives insight into the light-gathering capability, as well as the overall size and complexity of the system. The size of the FOV can indicate user priorities or system performance, such as tracking capability of the mount for SOI systems and star detection ability in OD systems that use celestial references for position measurements. A practical reason for using these two metrics is that often there were few other specifications given in the references.

It is instructive to mention which data points were not collected. The reported visual magnitude of observable objects was not used, since this is also a function of the local altitude and weather conditions. Often a source would associate an angular accuracy with the surveillance system, however these accuracies were ambiguous: sometimes referring to telescope pointing accuracy, star position data reduction accuracy, final orbit estimate accuracy, etc. Additionally, orbit estimate accuracy is influenced by the accuracy of the timing mechanism, which was outside the scope of this review.

The goal of this study was to emphasize data collection on a wide range of system, rather than presenting detailed information on each system. As such, this review is not exhaustive, but should serve as a useful reference for others wishing to learn more about a particular system or time period.

2. EARLY SYSTEMS: 1950 – 1970

Not surprisingly, the early history of optical space surveillance is dominated by references to the space race between the US and the Soviet Union, as well as efforts by many nations to support the International Geophysical Year. Many early systems were designed to undertake scientific research in geophysical and atmospheric fields.

2.1 LEO and GEO OD

The systems capable of tracking satellites were exclusive to government programs during this period (Table 1). These systems were typically the most advanced, and their ability to photograph dim satellites made them valuable space surveillance tools. The literature also include examples of these systems being used for scientific research.

Table 1. Early OD tracking systems

System	Aperture (m)	FOV (deg)	Segment
Baker-Nunn [1]	0.50	5 × 30	US Gov.
AFU-75 [2][3]	0.21	10 × 14	Foreign Gov.
SBG [4]	0.43	6 × 8	Foreign Gov.
FAS [2]	0.25	7 × 10	Foreign Gov.
VAU [2]	0.50	5 × 30	Foreign Gov.
Hewitt [5]	0.61	10	Foreign Gov.
Antares [2]	0.30	11	Foreign Gov.

Numerous visual and photographic systems were found that were non-tracking, often constructed from surplus aerial reconnaissance cameras and mounted on kinetheodolite or theodolite bases (Table 2). These systems often employed mechanical shutters to introduce breaks in the satellite trails. Most references involved geodetic, geopotential, or atmospheric studies. Despite some of these using sidereal tracking, they could not track a satellite to the same degree as those above.

There were also examples of pre-existing observatories in the USSR being adapted for satellite observations. Around 1958 the Alma-Ata observatory in Kazakhstan attached a photographic device on the existing 0.5-m Maksutov-type telescope to measure satellite positions, and two telescopes at the Crimean Astronomical Observatory in Ukraine and the 0.7-m telescope at the Abastumani Astrophysical Observatory in Georgia were used to observe Mars and Luna space probes in the late 1960s, though the range to the probes during the observations was not specified [6][7].

2.2 Amateur Involvement

Amateur groups across the world contributed to the early space surveillance needs. Moonwatch was a well known program organized by the Smithsonian Astrophysical Observatory, with similar groups operating in the USSR. In fact, a Moonwatch team in Australia made the first confirmed Sputnik observation on October 8, 1957, while the Baker-Nunn was still being assembled [8]. Another amateur group was the Western Satellite Research Network (WSRN) in the US, directed and coordinated by North American Rockwell. The WSRN made observations and estimated brightness for many spacecraft well into the 1960s, including Apollo spacecraft during translunar orbit phases. There is even a documented instance where the WSRN assisted in spotting the lost satellite 1960 Iota 4. Table 3 highlights some visual observing systems used by these groups [9][10].

Table 2. Early OD systems with fixed or limited tracking

System	Aperture (m)	FOV (deg)	Segment
BC-4 [6]	0.12	33 × 33	US Gov.
PC-1000 [11]	0.20	10 × 10	US Gov.
MOTS-24 [11]	0.10	--	US Gov.
MOTS-40 [11]	0.20	11 × 14	US Gov.
K-50 [11]	0.23	6.5 × 8.5	US Gov.
NAFA-3s-25 [7]	0.10	30 × 50	Foreign Gov.
NAFA-MK-75 [7]	0.21	--	Foreign Gov.
Geodetic Institute of Potsdam [4]	0.20	3.5 × 3.5	Foreign Acad.
Technische Hochschule [4]	0.30	5 × 5	Foreign Acad.
Poznan-2 [2]	0.14	6 × 8	Foreign Gov.
Geodetic Institute of Finland [2]	0.34	5 × 5	Foreign Acad.
French K-37 [12]	0.12	15 × 15	Foreign Acad.
Italian K-37 [13]	0.12	--	Foreign Acad.
Osservatorio Astronomico Privato [14]	--	6	Foreign Acad.
Astro-1 phototheodolite [15]	0.07	8	--
Utrecht University, small Schmidts [16]	0.12	20	Foreign Acad.
TZK Binocular [7]	0.08	7	Foreign Gov.
BMT-100 Binocular [7]	0.11	5	Foreign Gov.
UFISZ-25-2 Camera [7]	0.10	--	Foreign Gov.
Univ. of Wales, Aberystwth [17]	0.07	--	Foreign Acad.
Photo-electric Satellite Tracker [18]	0.15	10	Foreign Acad.
Geographical Survey Institute of Japan [19]	0.20	--	Foreign Gov.

Table 3. Representative amateur systems during early period

System	Aperture (m)	FOV (deg)
Moonwatch Monoscope [20]	0.05	12
Apogee Scope [6]	0.125	2.5
AT-1 Satellite Telescope [7]	0.05	11
WSRN Johannesburg reflector [10]	0.5	--

2.3 LEO SOI

Ref [21] provides an excellent review of optical SOI capabilities developed by the U.S. Air Force up until the 1980s. Preexisting long focal-length telescopes designed for missile launch support were used to characterize spacecraft soon after the launch of Sputnik in 1957. A site at Sulphur Grove, near Wright-Patterson Air Force Base, was established to conduct experiments on satellite optical characteristic and SOI technologies. One tool used in the 1960s was a 0.61-m f/16 Cassegrain telescope on a four-axis modified Baker-Nunn mount. Meanwhile a new site began construction in 1960 in New Mexico, which became the Cloudcroft Electro-Optical Facility, with first light in 1964. A 1.2-m Newtonian telescope on a 3-axis mount allowed tracking of LEO satellites. High-speed, short exposure film and high frame-rate television cameras were used to record uncompensated satellite images despite atmospheric distortion.

In 1962, the US Naval Ordnance Test Station in China Lake, California conducted upper atmospheric research using a photoelectric photometer system. A 0.27-m Schmidt telescope mounted on a surplus Askania-Werke KTh-40 kinetheodolite was used to track LEO satellites, with the observed light being filtered into blue, orange, and red wavelengths, each measured with a separate photomultiplier tube [22].

3. MIDDLE SYSTEMS: 1970 – 1990

This period did not have as many new systems as the preceding one, although there was a definite increase in GEO OD and LEO SOI activity.

3.1 LEO SOI

The SOI advances in the US continued in this period with the construction of the AMOS site between 1963 and 1969 in Maui. The first systems to be installed were the 1.6-m and the dual 1.2-m B29 and B37 systems. AMOS began operations in 1969, and the 1.2-m mount supported operational SOI missions in 1977 [21].

3.2 LEO and GEO OD

This period is also characterized by an increase in systems for GEO surveillance, which was difficult to achieve with radar. In the mid 70s, Massachusetts Institute of Technology's Lincoln Lab designed and built the Experimental Test System (ETS) in Socorro, New Mexico. The purpose of ETS was to develop optical space surveillance technologies for the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system planned by the US Air Force. GEODSS became operational in 1979 and replaced the Baker-Nunn cameras [23][24][25].

The 1970s and 80s saw some of the first attempts to observe and characterize the growing space debris problem, with most programs being supported by preexisting systems.

- Russian VAU and SBG (Table 1), GEO debris use around 1975 and 1977 [26].
- 0.4-m telescope of Main Astronomical Observatory, National Academy of Sciences of Ukraine, GEO debris use beginning 1983 [27].
- NASA + ETS, LEO and GEO debris research in 1980s [28][29].
- GEODSS also used in debris studies around 1989 [30][31].
- 0.9-m telescope at the University of Arizona, Tucson, was used in 1984 to determine the orbits of debris in GEO under NASA [32].

During this period, we also find examples of optical systems being evaluated for augmenting radar tracking and improving the orbit determination of satellites. Some of these systems were preexisting, whereas others were newly designed.

- In 1972, study using optical tracking data from the Russian AFU-75 and British Hewitt [33][34].
- In 1978, study by Okayama Astrophysical Observatory on SAKURA GEO satellite [35].
- Radio Research Lab 1983 study using ETS-III, U.S. Satellite Beacon Explorer-III data [36].
- Communication Research Laboratory of Japan, GEO tracking studies, 1989 [37].

3.3 Amateur Involvement

There were few examples of new amateur groups being formed in this period. A group called the Geodetic Satellite Watch was organized by the National Space Development Agency (NASDA) of Japan to support their Experimental Geodetic Satellite. These groups, along with NASDA, were to observe transit times and tracking angles using small photographic and TV fixed cameras [38].

4. LATER SYSTEMS: 1990 – PRESENT

After the relative lull of new systems during the 70s and 80s, this period saw a large increase in the number of systems, mostly attributable to the availability of cheap CCD sensors and computerized mount controls and data reductions methods. Highly capable COTS equipment for astronomy and video purposes were used in many government, academic, and amateur systems.

4.1. LEO SOI

New government SOI systems included US Air Force assets which, although capable of compensated imagery using adaptive optics and laser illumination of targets, used reflected sunlight during early operations. Other government systems performed SOI imagery of large LEO objects like MIR, ISS, and the Space Shuttle using CCD cameras to record at high frame rates and acquire resolved images despite atmospheric turbulence (a method which would be used by amateurs as well). These SOI systems are summarized in Table 4.

Table 4. Recent SOI systems

System	Aperture (m)	FOV (deg)	Segment
MSSS: Advanced Electro-Optical System* [39]	3.6	0.003**	US Gov.
Starfire Optical Range [40]	3.5	0.06	US Gov.
58-lb LEO Tracker, Boeing IRAD study [41]	0.20	0.14	US Gov.+
NAL LEO Debris Tracking Facility [42]	0.35	--	Foreign Gov.

* also documented use as LEO OD [43]
** smallest FOV for the Visible Imager sensor [44]
\+ actually a commercial system, but inspired by government work

4.2 LEO and GEO OD

This period saw an increase in the number of systems used for GEO OD, which coincided with increased interest in finding space debris in GEO (Table 5). The availability of large, sensitive CCDs and the fact that tracking requirements were easily satisfied with COTS astronomy mounts likely contributed to the trend. The use of COTS products was apparent in both government and academic systems.

Table 5. Recent GEO OD systems

System	Aperture (m)	FOV (deg)	Segment
James Gregory Telescope, Univ. St. Andrews* [45]	0.95	0.2 × 0.3	Foreign Acad.
PIMS [46]	0.4	0.6 × 0.6	Foreign Gov.
PIMS-FX [46]	0.1	3.8 × 3.8	Foreign Gov.
NAL Yatsugatake [42]	0.45	0.88	Foreign Gov.
Kashima Space Research Center [47]	0.35	0.6 × 0.4	Foreign Gov.
ESA Space Debris Telescope, Tenerife [48]	1.0	0.7 × 0.7	Foreign Gov.
Zimmerwald Telescope, Univ. of Berne [49]	1.0	0.5	Foreign Acad.
NAL GEO Debris Observation Facility [50]	0.35	3.2	Foreign Gov.
TT1 at Castelgrande Observatory, Univ. of Rome* [51]	1.51	0.01	Foreign Acad.
Rosace of CNES [49]	0.5	0.3 × 0.3	Foreign Gov.
MODEST of Univ. of Michigan [52]	0.6	1.3 × 1.3	US Acad.
Bisei Spaceguard Center 1-m [42]	1.0	2.5 × 3.0	Foreign Gov.
AMOS Phoenix (modified Baker-Nunn) [53]	0.5	6.8 × 6.8	US Gov.
TAROT of CNES [54]	0.25	1.9 × 1.9	Foreign Gov.
Crimean Astronomical Observatory (CrAO) AT-64, Ukraine* [55]	0.64	0.9 × 0.6	Foreign Gov.
CrAO 2.6-m ZTSh* [55]	2.6	0.1 ×x 0.1	Foreign Gov.
CrAO SR-220 [56]	0.22	2.8 × 2.8	Foreign Gov.
Central Astronomical Observatory (CAO), Russia, 65-cm [56]	0.65	0.2 × 0.2	Foreign Gov.
CAO SR-220 [56]	0.22	4.4 × 4.4	Foreign Gov.
CASTOR-A, Royal Military College of Canada [57]	0.36	--	Foreign Acad.
CASTOR-B, Royal Military College of Canada [57]	0.25	0.4 × 0.4	Foreign Acad.
Wide FOV (WFOV) Raven** [58]	0.5	5.0	US Gov.
MCAT** [58]	1.0	2.0	US Gov.
NASA CCD Debris Telescope, Cloudcroft, NM [59]	0.32	1.7 × 1.7	US Gov.

* pre-existing astronomical telescope
** still in planning in cited reference

There were fewer examples of LEO debris systems, mostly attributable to the availability of radar at these altitudes. The 3-m Liquid Mirror Telescope, under the Orbital Debris Program Office at NASA, used fixed zenith staring to detect LEO objects [60]. The Bisei Spaceguard Center, which was created by the Japanese government to track near-Earth asteroids and space debris, also used 0.25-m and 0.5-m telescope systems to observe LEO objects [61].

The literature also contained references of ground-based observatories being used to observe deep-space probes during this time period. In 2002, NASA's CONTOUR spacecraft suffered an anomaly while injecting into a heliocentric orbit. After losing contact, pieces of the spacecraft were observed by the Spacewatch 1.8-m telescope, the LINEAR facility in NM, the University of Hawaii 2.24-m telescope on Mauna Kea, and the Jet Propulsion Laboratory's 1-m telescope in CA, which helped determine the trajectory and suggest a breakup [62]. Similarly in late 2002, optical observations of the Japanese NOZOMI Mars spacecraft during an Earth swingby were used to verify the spacecraft's orbit estimates, which had poor high-gain antenna pointing due to attitude failures [63].

4.3 Amateur Involvement

Amateur systems using similar CCD video cameras acquired SOI images of large LEO objects, often times writing custom computerized tracking programs to control the telescopes. Table 6 shows some published examples, but there are surely other undocumented systems.

Table 6. Recent amateur SOI systems

System	Aperture (m)	COTS aspects
Gilliland Observatory [64]	0.3	Meade Schmidt-Cassegrain, Archimage mount, GW-100N Neptune astro video camera
Masding-Tyrrell [65]	0.25	Meade LX200 Scmidt-Cassegrain, JVC digital camcorder
Huber-Lindemann [65]	0.4	Munich Public Observatory telescope, Panasonic camcorder
Cash [65]	0.24	Celestron Ultima, Phillips Vesta Pro webcam

Like the other two time frames discussed previously, another amateur group was found in the literature. The SeeSat-L group is an internet forum specializing in satellite observation predictions and sharing technical knowledge related to satellite tracking. In one instance, the forum assisted in observing the tumbling ABRIXAS satellite [66].

5. DATA ANALYSIS

Fig. 1 through 3 show the compiled metrics for the above mentioned systems. The times on the horizontal axes correspond to the approximate year in which each system became operational. Sometimes the start year was not obvious from the literature, so the date of a particular research experiment was used instead. If instances were found where considerable upgrades or operational changes were made to a system, it was reentered into the database. It would have been desirable to also include when systems ceased operations, but few of the references specified those dates.

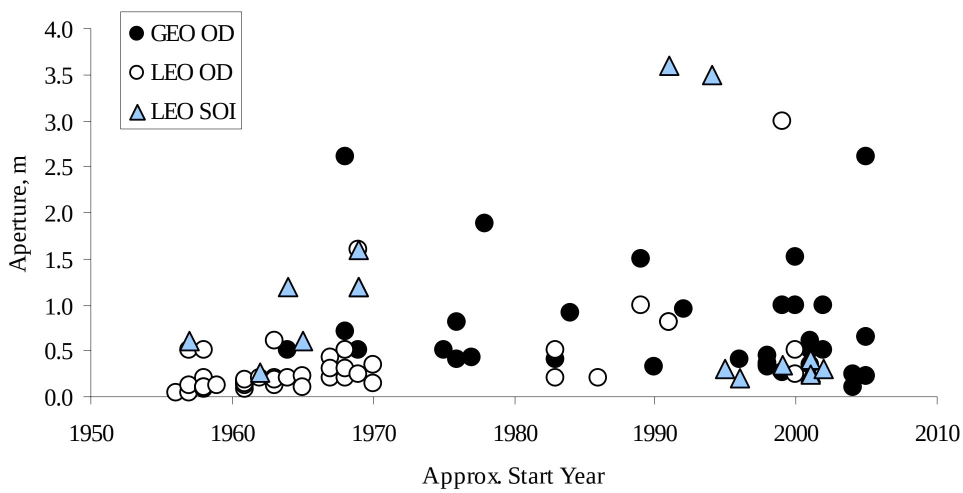

Fig. 1. Plot of aperture by start year, separated by use

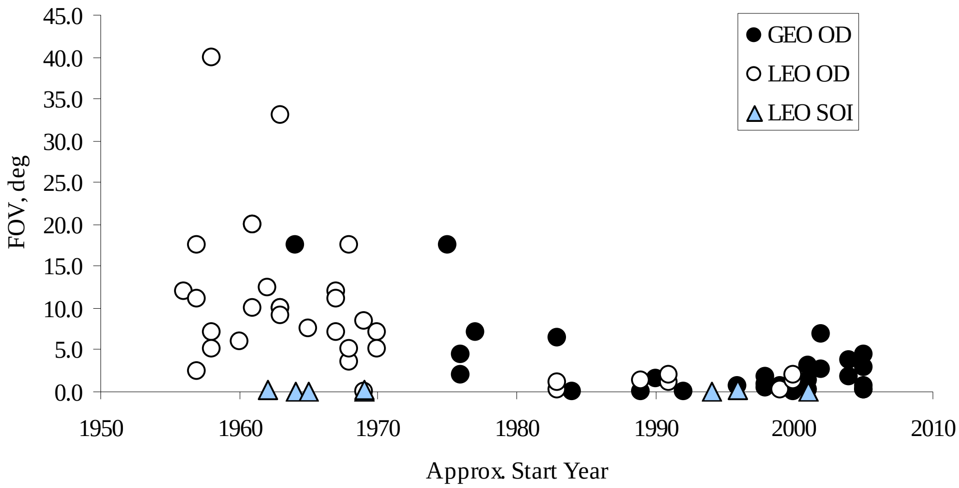

Fig. 2. Plot of FOV by start year, separated by use

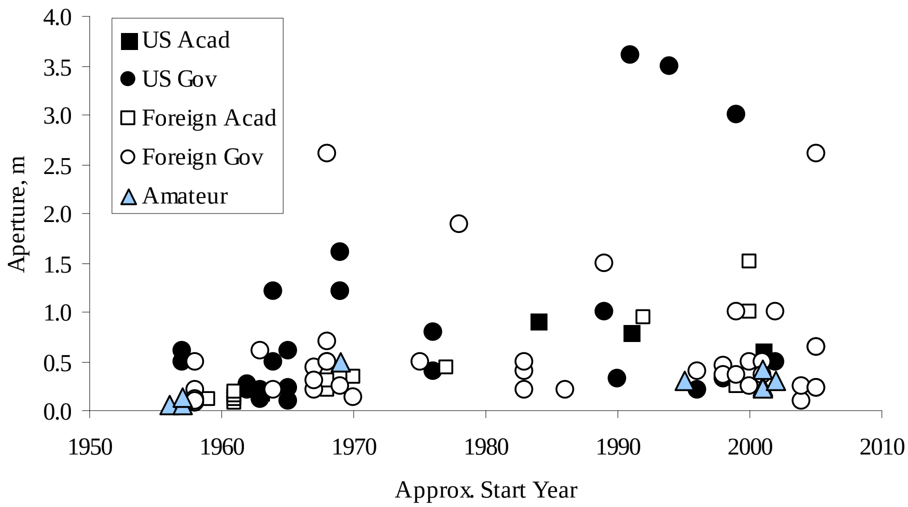

Fig. 3. Plot of aperture by start year, separated by industry segment

Fig. 1 and 2 show the early emphasis on LEO, followed by the later interest in GEO. Fig. 1. shows that LEO SOI systems tended to increase in aperture until the mid-1990s. This drop in SOI system aperture reflects the rise in amateur and other segments using COTS equipment to image large LEO objects. Fig. 1 and 2 show that LEO OD systems increased in aperture but decreased in FOV, possibly suggesting that tracking mounts became more capable to allow larger telescopes to be tracked to greater accuracy. However, since some of these LEO OD studies used zenith staring modes, this assertion cannot be made using these results alone. It is striking to compare the small FOV in SOI versus OD systems, but this result is expected from the high magnification requirements of typical SOI missions.

In general, Fig. 2. does show an overall decrease in FOV, with a slight increase in recent years. This trend in FOV reflects the fact that GEO objects move at a slower apparent velocity compared with LEO objects, which allows users to focus on a much narrower portion of the sky. The slight rise in GEO FOV capability recently is probably attributed to a renewed interest in detecting undiscovered GEO debris, which would benefit from a larger search area.

Fig. 3 suggests that US government systems tend to have higher aperture, but foreign government systems are not far behind. This plot also shows that US and foreign systems appear in roughly equal numbers during the various time periods discussed previously, with a slight rise in the number of foreign systems in recent years.

6. CONCLUSION

A brief historical overview of perceived trends in ground-based telescopes for space surveillance over the past 50 years has been provided. Each time period was introduced briefly, and by focusing on aperture and FOV as two metrics which were commonly reported in the literature, design trends have been highlighted. Because this review has surely missed certain systems, the reader is encouraged to use the current study as a starting point for future investigations. Likewise, at least one reference is given for each system, but others exist and may shed additional light on particular systems.

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