Detection in Deep Space from the Southern Hemisphere of Near-Earth Objects using a Combined Radar/Optical System

Ed Kruzins[1,2], Lance A.M.Benner[3], Melrose Brown[1], David Coward [5], Guifre Molera Calves[4], Philip G.Edwards[2], Jon D.Giorgini[3], Steve Guedon[1] Shinji Horiuchi[2], Bruce Gendre[5,6], John Kennewell[5,7] Andrew Lambert[1], T.Joseph Lazio[3], Benjamin Listen[5,6], John Moore[5], Dorota Mieczkowska [5,8] Edwin Peters[1], Chris J.Phillips[2], Tom Riddell[1], Jamie Stevens[2], Arie Verveer[5]

[1] *University of New South Wales, Canberra, Australia,*
[2] *Commonwealth Scientific and Industrial Research Organisation, Sydney, Australia,*
[3] *Jet Propulsion Laboratory, California Institute of Technology. Pasadena, California, USA,*
[4] *University of Tasmania, Hobart, Tasmania, Australia,*
[5] *University of Western Australia, Perth, Western Australia, Australia,*
[6] *Australian Research Council Centre of Excellence for Gravitational Wave*
[7] *Discovery(OzGr). Australian Space Academy Meckering, Western Australia,*
[8] *Polish Space Agency, Trzy Lipy 3 Street, 80-172 Gdańsk, Poland*

ABSTRACT

We describe further research by the Southern Hemisphere Asteroid Radar and Optical Program, to characterise near-Earth asteroids and objects (NEO's) of interest. Apollo and Aten class asteroids represent another form of deep space debris of a potentially hazardous nature. The Southern Hemisphere Asteroid Radar Program (SHARP) located in Australia uses the facilities of the Deep Space Network located in Canberra (CDSCC), the CSIRO Australia Telescope Compact Array (ATCA) 22m antennas at Narrabri and the 12m University of Tasmania antennas at Hobart (Tasmania) Australia. Optical telescopes located at the University of New South Wales (UNSW) and University of Western Australia (UWA) show how small 0.3-1.0m apertures can be combined into a radar/optical NEO detection system located exclusively in the southern hemisphere. We discuss progress on STEM education and student research topics including asteroid signal refinement, simulations, signal correlations and Stokes Vector Decomposition of NEO radar echo polarisations to determine if the complex I, Q, U, V components can be set into algorithms to offer additional insights into NEO characteristics. These non-imaging techniques might also be applied to human made objects to support deep space domain awareness.

Introduction

For many years, space agencies and institutions have observed and monitored near Earth asteroids and objects (NEO's) using high gain radio frequency antennas and optical telescopes in the northern hemisphere (GSSR, Arecibo, Catalina, Pan-STARRS, ATLAS and LINEAR) (1). However, a regular operational system to monitor the southern skies does not have the same level of maturity and is where a percentage of asteroids and various human made objects are not detected until they pass into northern skies [3,4]. The addition of southern hemisphere observations was a next logical step.

The Southern Hemisphere Asteroid Radar/Optical Program

In 2015 the Southern Hemisphere Asteroid Radar Program (SHARP) [2] began its first radar observations using available antenna time on the 70m and 34m beam waveguide antennas located at the Canberra Deep Space Communication Complex (CDSCC). This was soon joined by the University of Tasmania (UTAS) in 2021 with their array of 12m, 26m and 30m radio telescopes. In 2022 SHARP was joined by the optical telescopes of the University of New South Wales (Viper and Falcon) and University of Western Australia (Falcon and Zadko) with their group of 0.3-1.0m optical telescopes extending the geographic observation capability from the east to west coasts of Australia. The Falcon telescope is a USAFA network managed by the respective universities.

Figure 1. Radar and Optical Telescopes of the Southern Hemisphere Asteroid Radar/Optical Program.

NEO Target Observations

The intent of the Southern Hemisphere Asteroid Radar/Optical Program is to observe asteroids simultaneously in both radar and optical. Observations by the Southern Hemisphere Asteroid Radar/Optical Program have included Apollo and ATEN class NEO's because of their Earth orbit crossing nature and classification as potentially hazardous asteroids (PHAs).

Since 2015 approximately 35 asteroids have been observed, with the early years up to 2022 dominated by the bistatic radar composed of the 70m antenna at CDSCC and the 64m Murryang (Parkes) and 6x22m ATCA radio telescopes located at Narrabri Australia.

Asteroid	Class	Date	Approx Dia m	Range LD	Sensors
2005 UL5	Aten	2015 Nov	250 m	6	Radar, CDSCC, Parkes & ATCA
1998 WT24	Aten	2015 Dec	400 m	11	Radar, CDSCC, Parkes & ATCA
3122 Florence	Amor	2017 Sep	5000 m	18	Radar, CDSCC & ATCA
2012 TC4	Apollo	2017 Oct	10 m	0.1	Radar, CDSCC & ATCA
2002 AJ129	Apollo	2018 Feb	700 m	10	Radar, CDSCC & ATCA
2010 WC9	Apollo	2018 May	80 m	0.5	Radar, CDSCC & ATCA
2003 SD220	Aten	2018 Dec	700 m	7	Radar, CDSCC & ATCA
2019 EA2	Aten	2019 Mar	30 m	0.8	Radar, CDSCC & ATCA
2019 GC6	Apollo	2019 Apr	20 m	0.5	Radar, CDSCC & ATCA
2019 SP3	Apollo	2019 Oct	33 m	0.97	Radar, CDSCC & ATCA
1966-084B (2020 SO)	Artificial	2020 Nov	10 m	0.5	Radar, CDSCC & ATCA
2020 XX3	Apollo	2020 Dec	7 m	0.15	Radar, CDSCC & ATCA

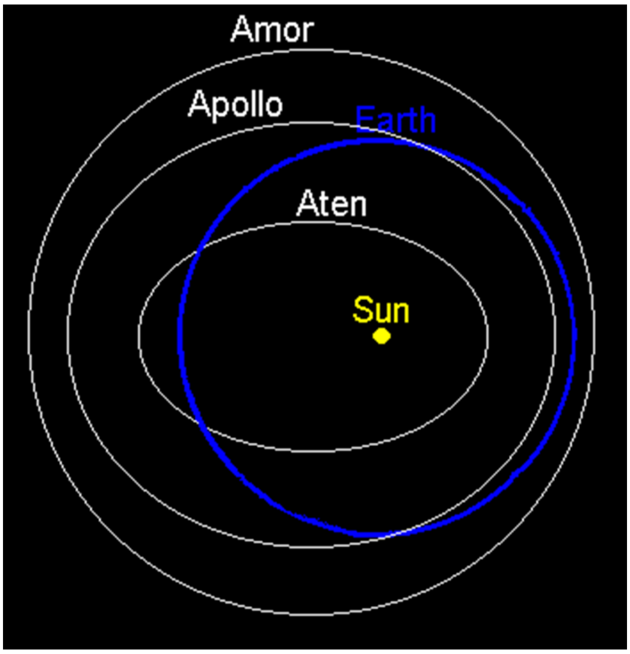

Table 1. Selection of NEO targets observed by the Southern Hemisphere Asteroid Radar Program (SHARP) 2015 to 2020 [5,6]. Right image courtesy of https://www.spacesettlement.com/apollo-amor-aten-near-earth-asteroids.html

Asteroid	Date	Approx Dia. Km	Range LD	Sensors PHA (Potentially Hazardous Asteroid)
2005 LW3	2022 Nov 22-23	0.15	4.3	Observed in Radar and optical, PHA
2015 RN35	2022 Dec 14-15	0.08	2.1	Observed in optical , PHA Candidate for a space mission
2014 HK129	2022 Dec 19-20	0.19	7.0	Observed in Radar, PHA
2010 XC15	2022 Dec 26-27	0.17	2.8	Observed in optical, PHA
2011 AG5	2023 Feb 2-3	0.16	4.7	Observed in Radar and optical, PHA Candidate for a space mission
2005 YY128	2023 Feb 15-16	0.95	12.1	Observed in Radar and optical PHA
2023 DZ2	2023 Mar 22-25	0.07	0.4	Rapid response, observed in radar, optical, PHA
2012 KY3	2023 Apr 13	0.66	12.8	Observed in Radar and optical PHA
2006 HV5	2023 Apr 27 -28	0.31	7.0	Observed in Radar, PHA
1994 XD	2023 Jun 9-10	0.48	14.8	Observed in Radar and optical, PHA
2018 UY	2023 Jul 11-12	0.24	7.8	Observed in Radar and optical, PHA
2020 UQ3	2023 Jul 15-16	0.06	7.4	Observed in Radar, PHA
2016 LY48	2023 Sep 17-18	0.18	4.3	Large pointing uncertainties?

Asteroid	Date	Approx Dia. Km	Range LD	Sensors PHA (Potentially Hazardous Asteroid) NHATS (Near earth Human Spaceflight Accessible Target
2011 GA	2023 Oct 14,15	0.22	7.0	Observed in radar, optical, PHA
1998 HH49	2023 Oct 16,17	0.17	3.5	Observed in optical , PHA Candidate for a space mission
2003 UC20	2023 Nov 1,2	1.90	13.6	Observed in Radar, optical NHATS, PHA
2001 QQ142	2023 Dec 5,6	0.70	14.4	Observed in radar, PHA
2008 OS7	2024 Feb 2,3	0.22	7.7	Observed in radar and optical, PHA
2013 NK4	2024 April 14,15	0.59	8.9	Observed in radar and optical PHA
2011 UL21	2024 Jun 27,28	2.2	17.1	Observed in radar and optical, PHA
2024 MK	2024 Jun 28,30	0.2	0.75	Rapid response. Observed in radar and optical, PHA
2012 OD1	2024 Jul 23,25	0.66	221	Planned PHA
2020 GE	2024 Sep 22,23	0.01	1.6	Planned NHATS, PHA
1998 ST7	2024 Oct 11,12	0.40	9.3	Planned Binary, PHA
2020 UL3	2024 Nov 11,12	0.10	4.3	Planned PHA
2006 WB	2024 Nov 26,27	0.10	2.3	Planned NHATS

Table 2. Selection of NEO targets observed by Southern Hemisphere Asteroid Radar/Optical Program 2022-2024.

NEO Target Analysis

We utilise simultaneous observation of asteroids in bi-static radar and optical telescopes to compare the centre frequency (A) shift of the echo spectrum and optical range rate to obtain insights into asteroid position and velocity. The broadening of the radar echo spectral peak (B) and the polarisation ratio μc =Sc/Oc (D/C), offers insights into rotation period, axis of rotation, size and surface roughness of the asteroid when combined with optical observations light curves.

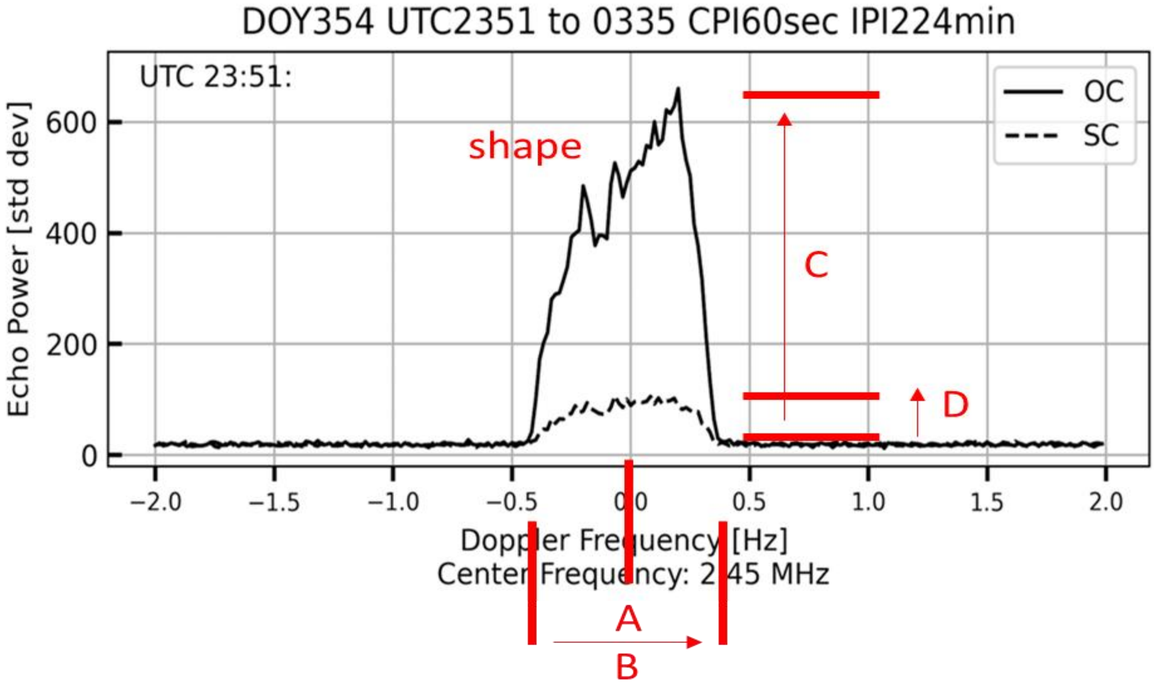

Figure 2. Example refined radar echo spectra of asteroid 2003 SD220 to demonstrate the anatomy of the signal and parameters measured such as centre frequency shift (A), doppler broadening (B) and polarisation ratio (D/C) whilst the shape of the peak offers potential insights into the irregularity of the asteroid from a spherical shape. Courtesy S.Darwell UNSW.

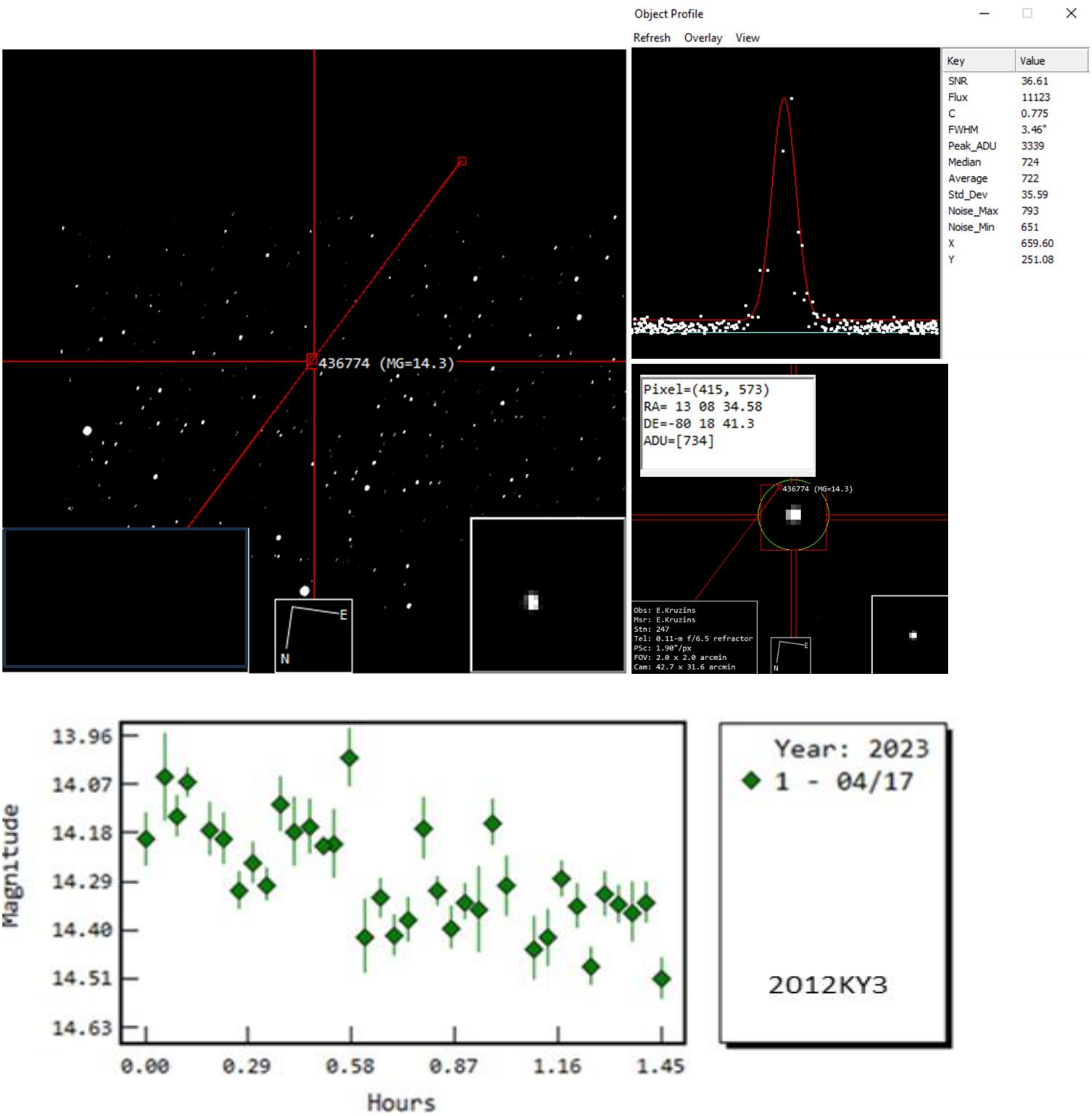

Figure 3. Example of the use of a small 0.11m aperture refractor telescope located at UNSW indicating optical asteroid image, trajectory, object profile and short-term light curve of asteroid 2012 KY3 observed 16 April 2023 exposure 25sec.

Asteroid class and composition have been shown to be correlated to circular polarisation ratio [7] and leads to insights related to the formation and histories of the object. The Stokes vector (S) can be written as composed of I, Q, U, V elements which are themselves functions of the radar echo electrical field "E" for left and right circular polarisation as shown in equation 1.

$$\boldsymbol{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad \text{where} \quad \begin{aligned} \mathbf{I} &= |E_l|^2 + |E_r|^2 \\ \mathbf{Q} &= 2Re(E_l^* E_r) \\ \mathbf{U} &= -2Im(E_l^* E_r) \\ \mathbf{V} &= |E_r|^2 - |E_l|^2 \end{aligned} \qquad (1)$$

Functions of the Stokes vector I, Q, U, V elements shown in equations 2,3,4

$$\frac{Sc}{Oc} = \mu_C = \frac{I+V}{I-V} \qquad (2)$$

$$m = \frac{\sqrt{Q^2+U^2+V^2}}{I} \qquad (3)$$

$$\chi = \arcsin\left(\frac{V}{mI}\right) \qquad (4)$$

provides the circular polarisation ratio (μ_C), degree of polarisation (m) and ellipticity (chi) of the radar echo signal. Advanced polarimetry using Stokes vector decomposition has been shown to indicate some of the physical properties of the asteroid including shape [8], ice content [9], surface roughness (eg boulders) and viewing geometry [10]. The fusion of optical data to the above remains a rich area of work being undertaken in this program.

STEM Education

The Southern Hemisphere Asteroid Research student program includes graduate and post graduate students under a program of research supported by supervisors and mentor groups located at UNSW, UWA, CSIRO and NASA JPL.

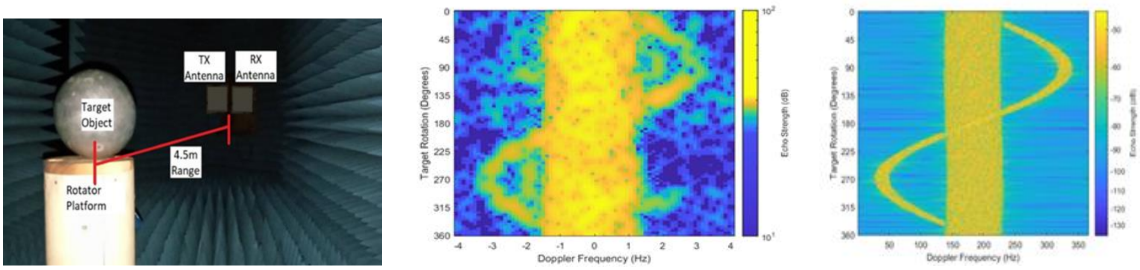

Figure 3. Simulated radar echo waterfall diagrams from a model illuminated within an anechoic chamber compared to the digital spherical model with a small orbiting companion. Courtesy C.Workman UNSW.

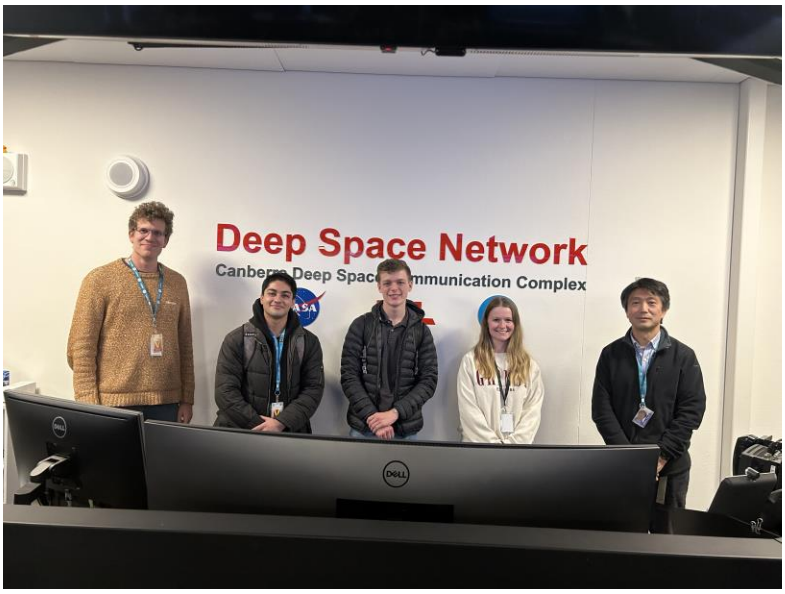

Figure 4. STEM Education Students (Blake Molyneux, Isabelle Saville-Brown, Emi Cashman ANU, Asha Wiltshier, Aakash Joshi, Callum Workman, Steve Guedon and Tom Riddell (UNSW) and Supervisors (Dr Shinji Horiuchi CSIRO, Dr Edwin Peters UNSW)

Student projects currently include optimising the processing of asteroid radar echoes**,** examining asteroid polarisations through Stokes Vector Analysis and comparing simulated asteroid echo signals with hard models in an anechoic chamber to digital models and real echo data from radar observations.

Summary

The Southern Hemisphere Asteroid Radar and Optical Program continues to monitor and measure near-Earth Apollo and Aten class asteroids. It highlights the importance of comparing radar and optical data to infer asteroid characteristics and the importance of a collaborative approach to obtain rich radar and optical data sets to enlarge methods of analysis.

The work highlights a vibrant STEM education and student research program including asteroid signal refinement, simulations, signal correlations and Stokes Vector Decomposition of NEO radar echo polarisations. Finally, it underscores the value of asteroid observations from the southern hemisphere and the use of this view to fill the asteroid monitoring gap for new asteroids that may arise from the southern ecliptic.

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