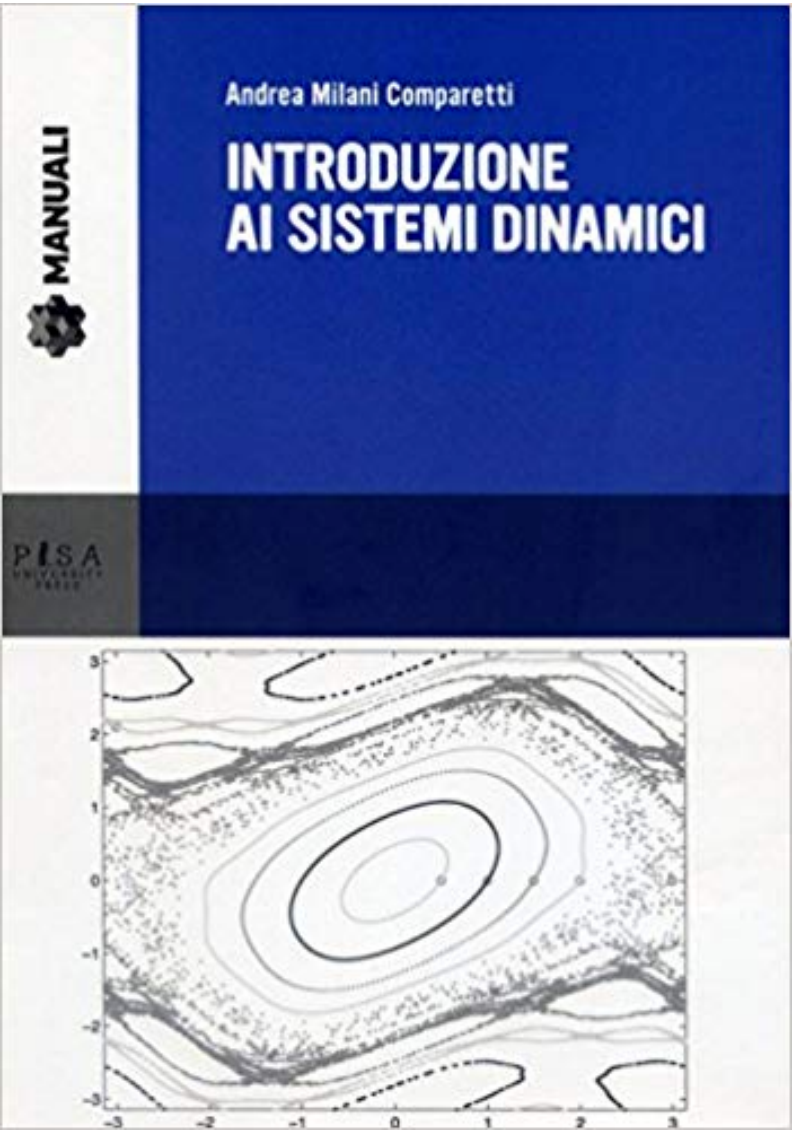
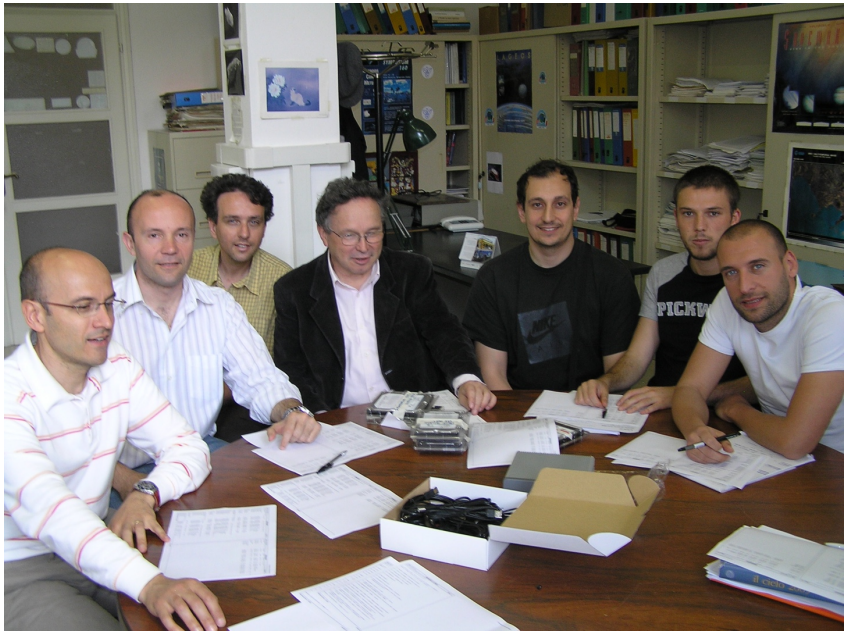
The tale of three small impacting asteroids

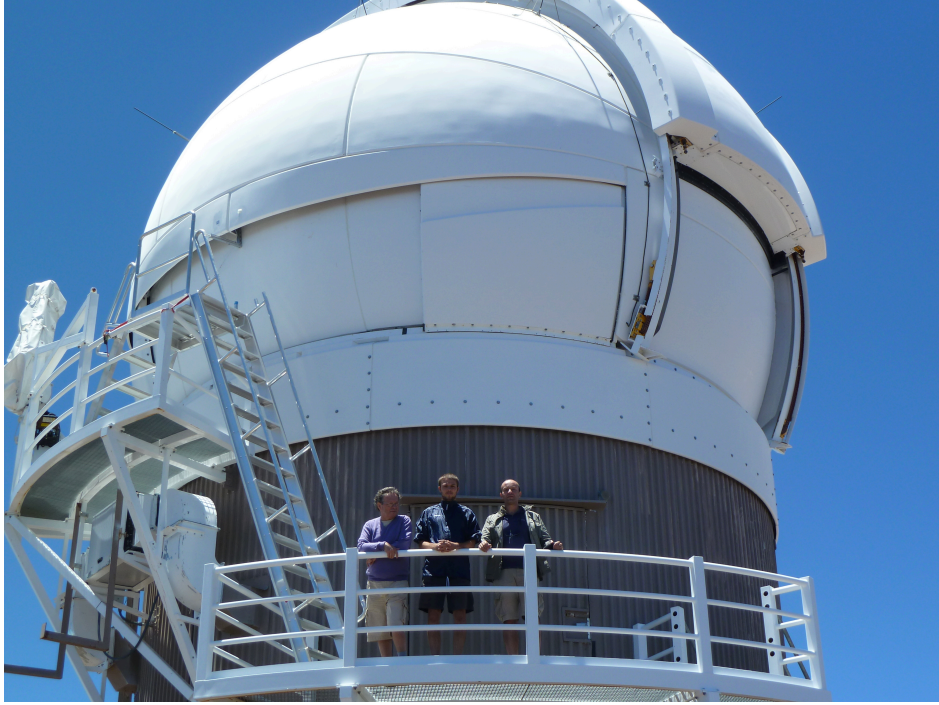
D. Farnocchia, S. Chesley, P. Chodas, E. Christensen,
R. Kowalski, P. Brown, P. Jenniskens

Jet Propulsion Laboratory
California Institute of Technology


MANUALI
Andrea Milani Comparetti
INTRODUZIONE
AI SISTEMI DINAMICI
PISA



RESCUE



The reason, in my opinion, is that Davide does not understand the deep mathematics of the problem

The reason, in my opinion, is that Davide does not understand the deep mathematics of the problem (maybe he has really become an engineer after all)

CASSA
DI RISPARMIO
DI LUCCA

Astron. Astrophys. 346, L65–L68 (1999)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Close approaches of asteroid 1999 AN_{10}: resonant and non-resonant returns

Andrea Milani[1], **Steven R. Chesley**[1], **and Giovanni B. Valsecchi**[2]

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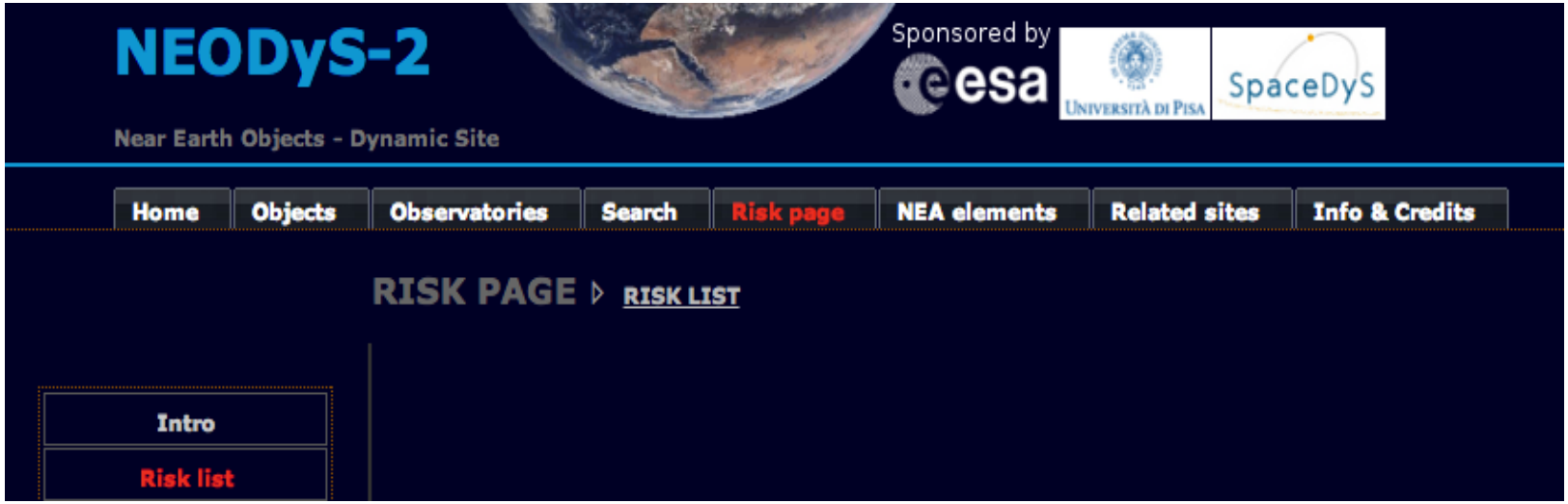
Received 13 April 1999 / Accepted 14 May 1999

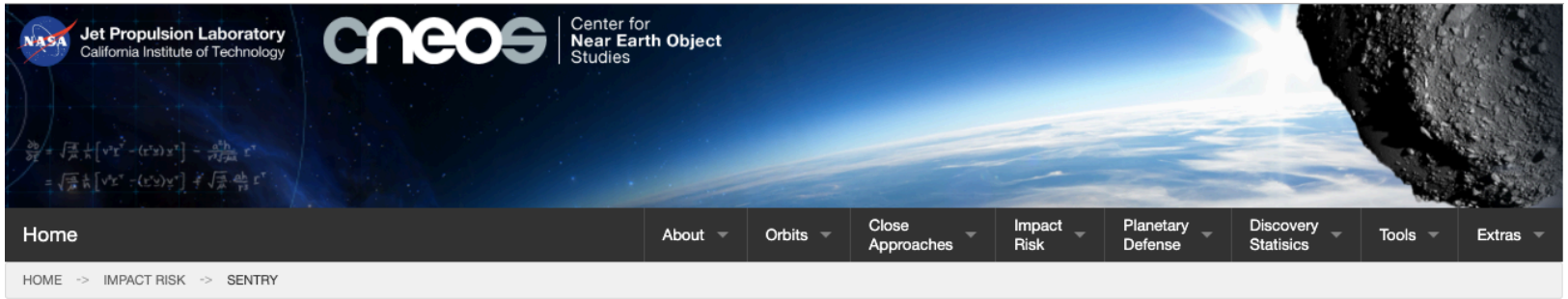
Abstract. The Earth passes very close to the orbit of the asteroid 1999 AN_{10} twice per year, but whether or not this asteroid can have a close approach depends upon the timing of its passage across the ecliptic plane. Among the possible orbits there are some with a close approach in 2027. The period of the asteroid may be perturbed in such a way that it returns to an approach to the Earth at either of the possible encounter points. We have developed a theory which successfully predicts the 25 possible such returns up to 2040. We have also identified 6 more close approaches resulting from the cascade of successive returns. Because of this extremely chaotic behaviour there is no way to predict all possible approaches for more than a few decades after any close encounter, but the orbit will remain dangerously close to the orbit of the Earth for about 600 years.

Key words: minor planets, asteroids – chaos

than the ones of the nominal orbit (Milani 1999). The region of these compatible solutions can be approximated by an ellipsoid of confidence, which, for a σ value up to 3, contains solutions with RMS of the residuals up to 0.63 arc-sec.

The nominal solution undergoes a close approach in August 2027 with a minimum distance from Earth's center of 0.025 7 AU. The plane normal to the geocentric velocity at closest approach is the Modified Target Plane (Milani & Valsecchi 1999). The hypothetical objects filling the confidence region evolve along a bundle of orbits; their intersections with the MTP define the confidence region of the encounter. If the Earth is not touched by this confidence region, then a collision can be ruled out. The confidence regions are very thin, the width being only 2 600 km, and 0.42 AU long. Thus the occurrence of a very close approach is not very likely: the true orbit could be anywhere along a very long line, including long stretches corresponding to very shallow encounters.

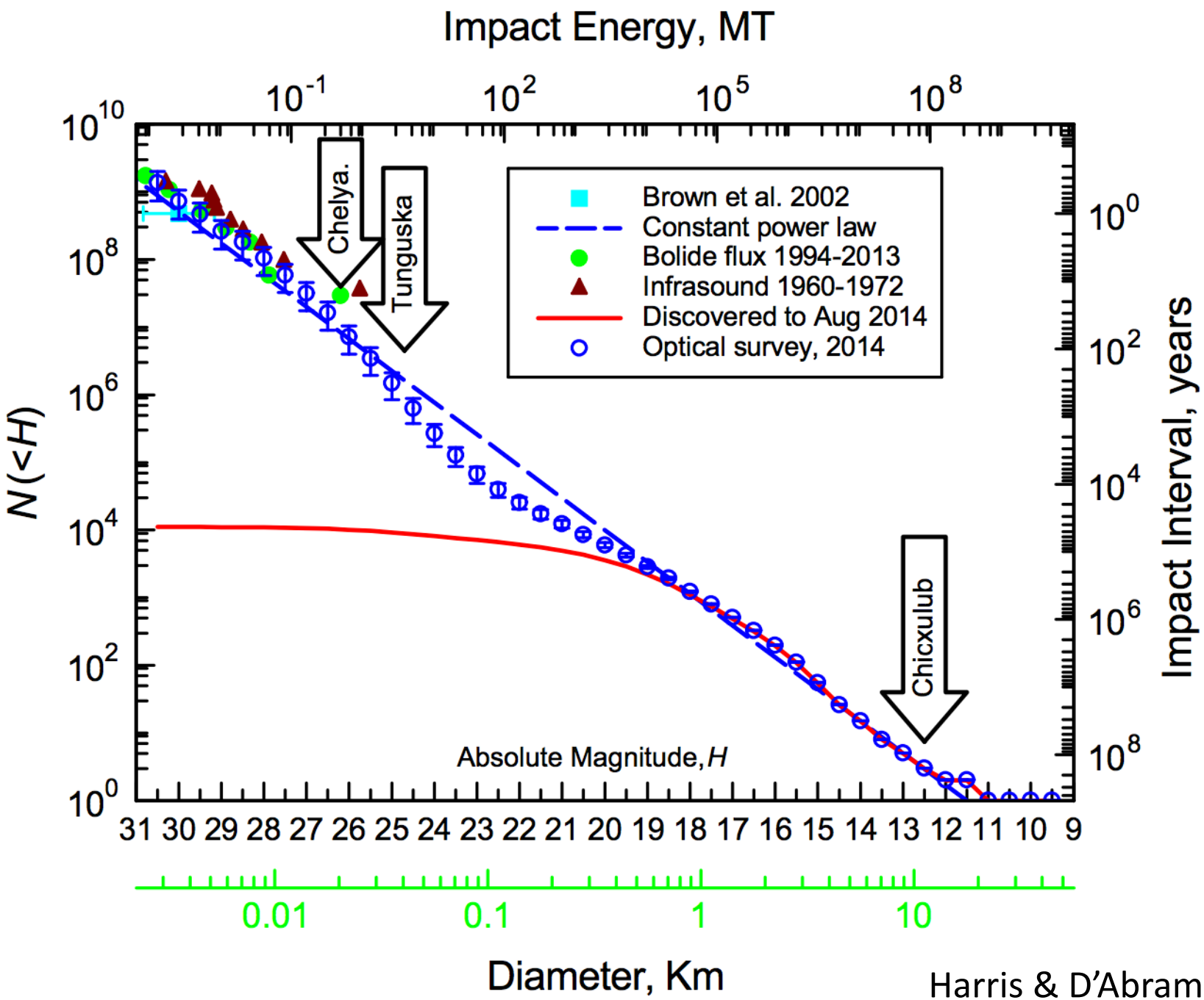




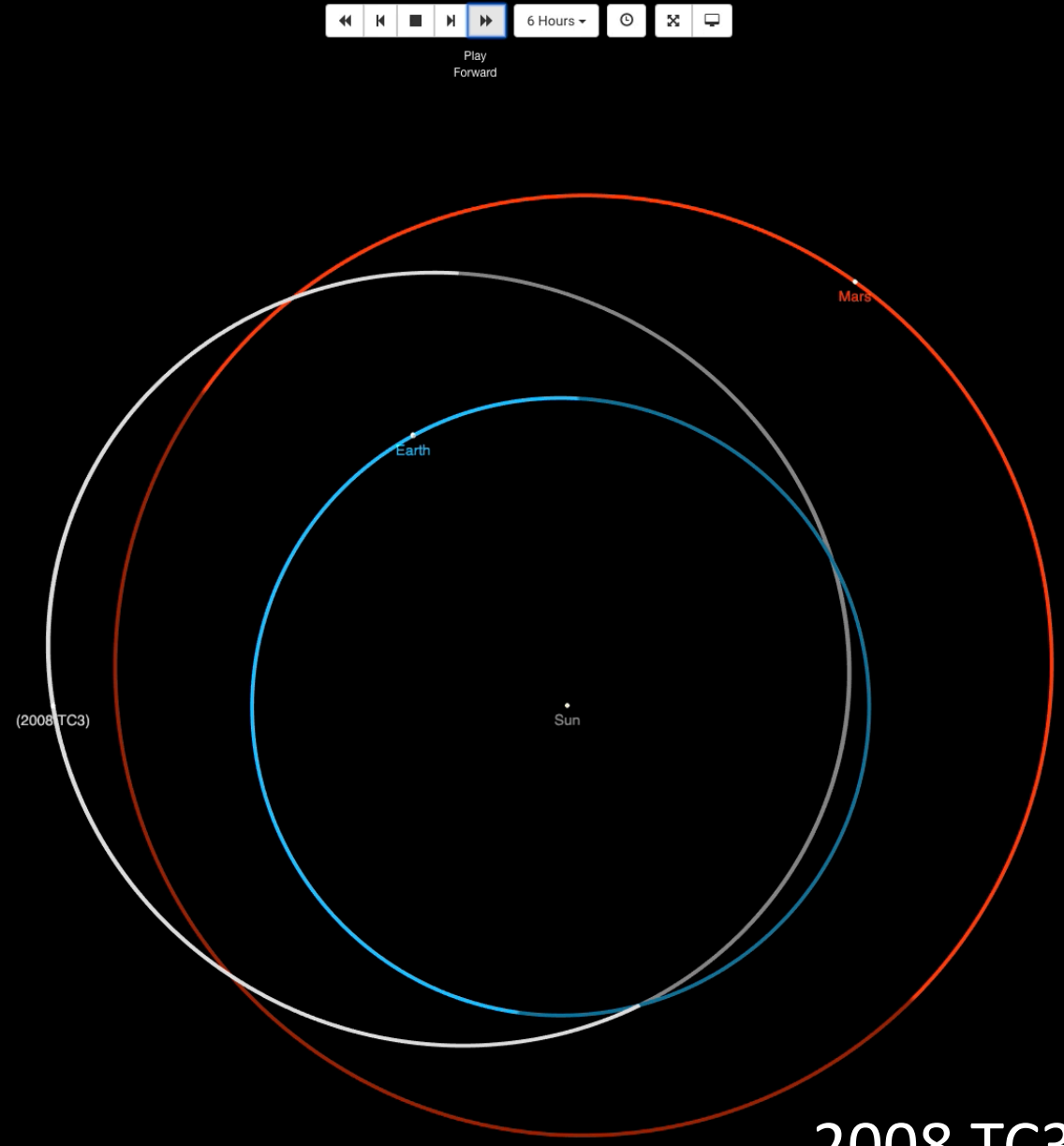
Sentry: Earth Impact Monitoring

Introduction | Object Table | VI Table | FAQ | Operational Notes | Removed Objects

Impact Risk Data



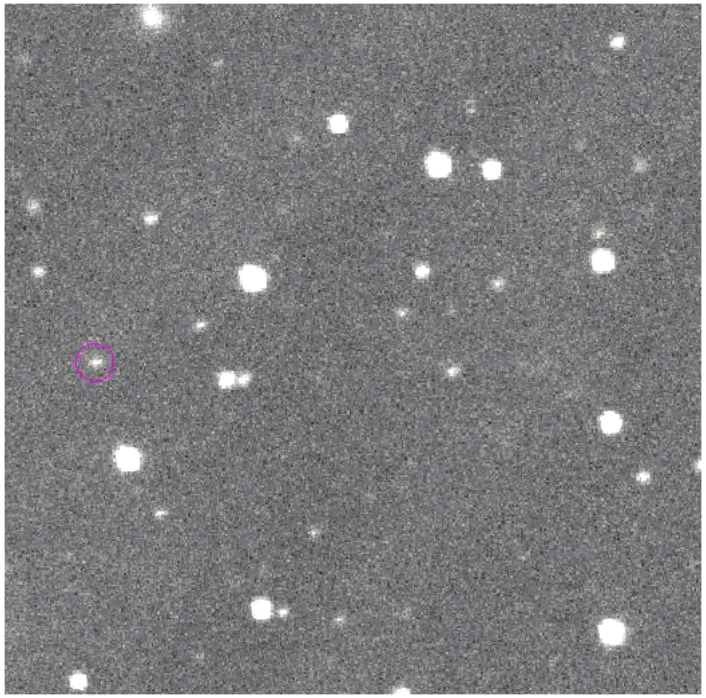
Harris & D'Abramo, 2015



2008 TC3

Oct. 7, 2008

Discovery



Size 4 m

R. Kowalski, Catalina Sky Survey

20 h before impact on Oct. 7, 2008

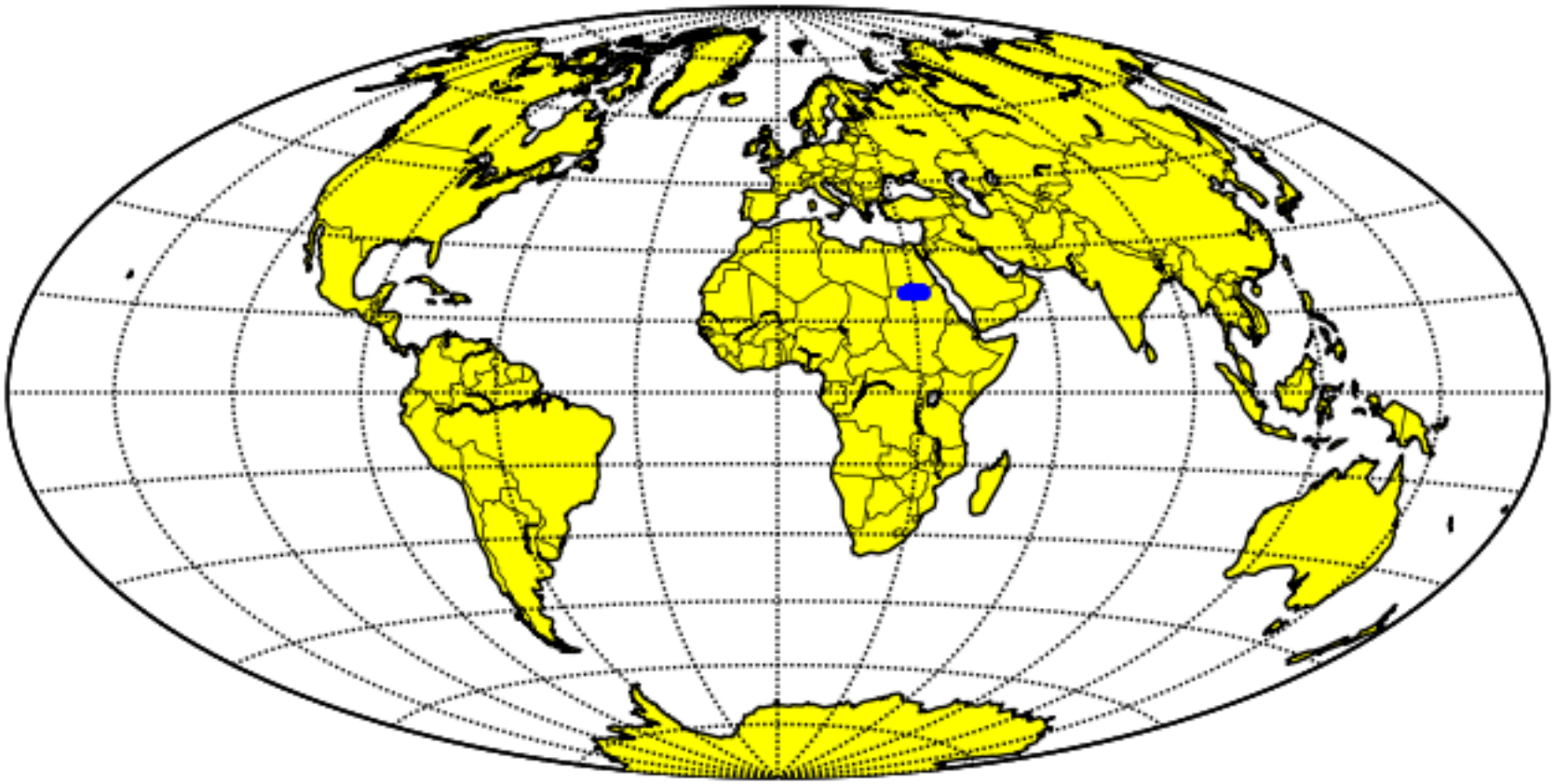
4 observations over 43 min

Follow-up by Kowalski, Sabino Canyon, Moorook, Siding Spring

Announced by MPC 12 h before impact

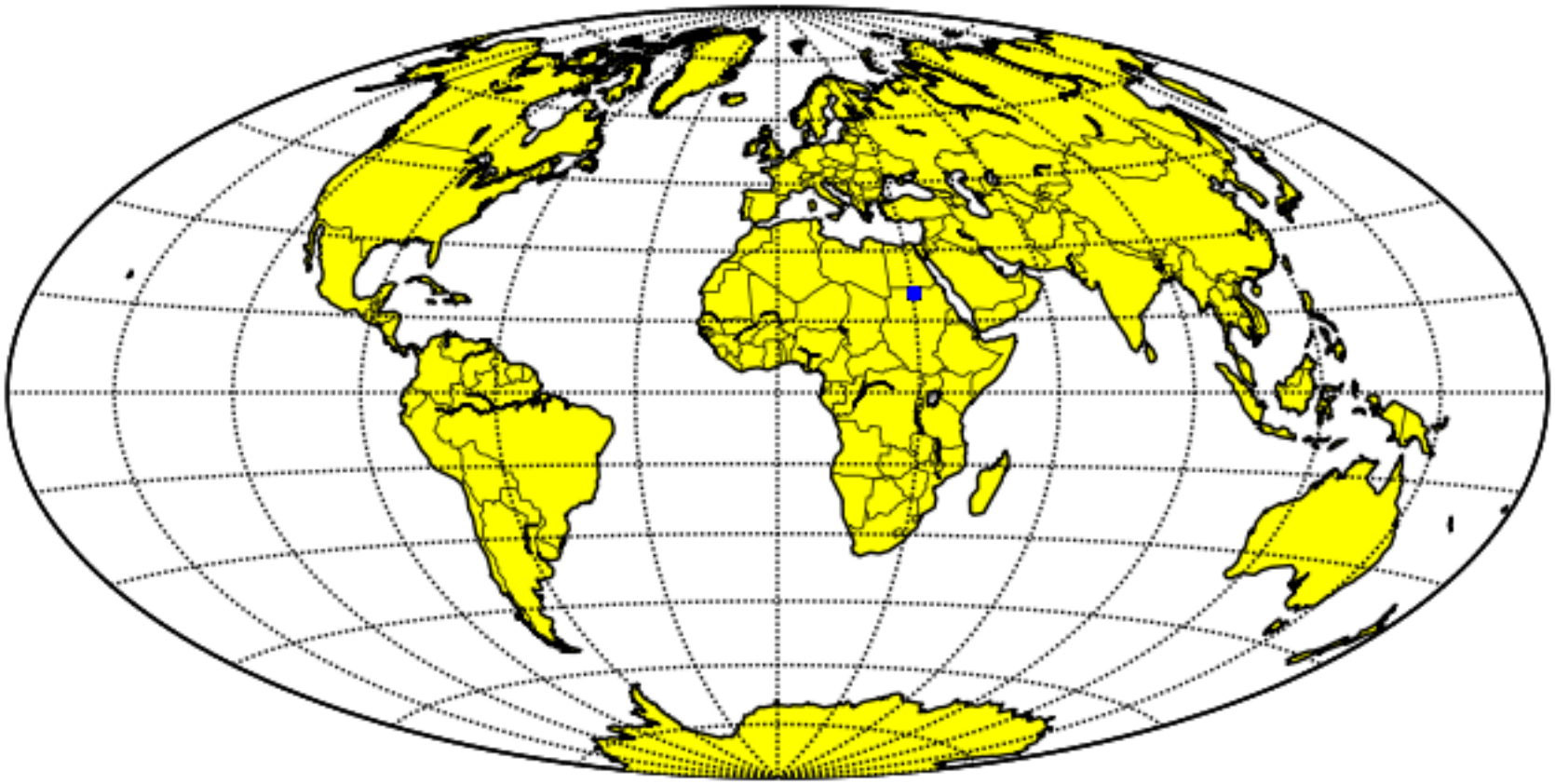
Impact prediction evolution

18 observations over 8 h 05 min
12 h to impact
Impact probability 100%



Impact prediction evolution

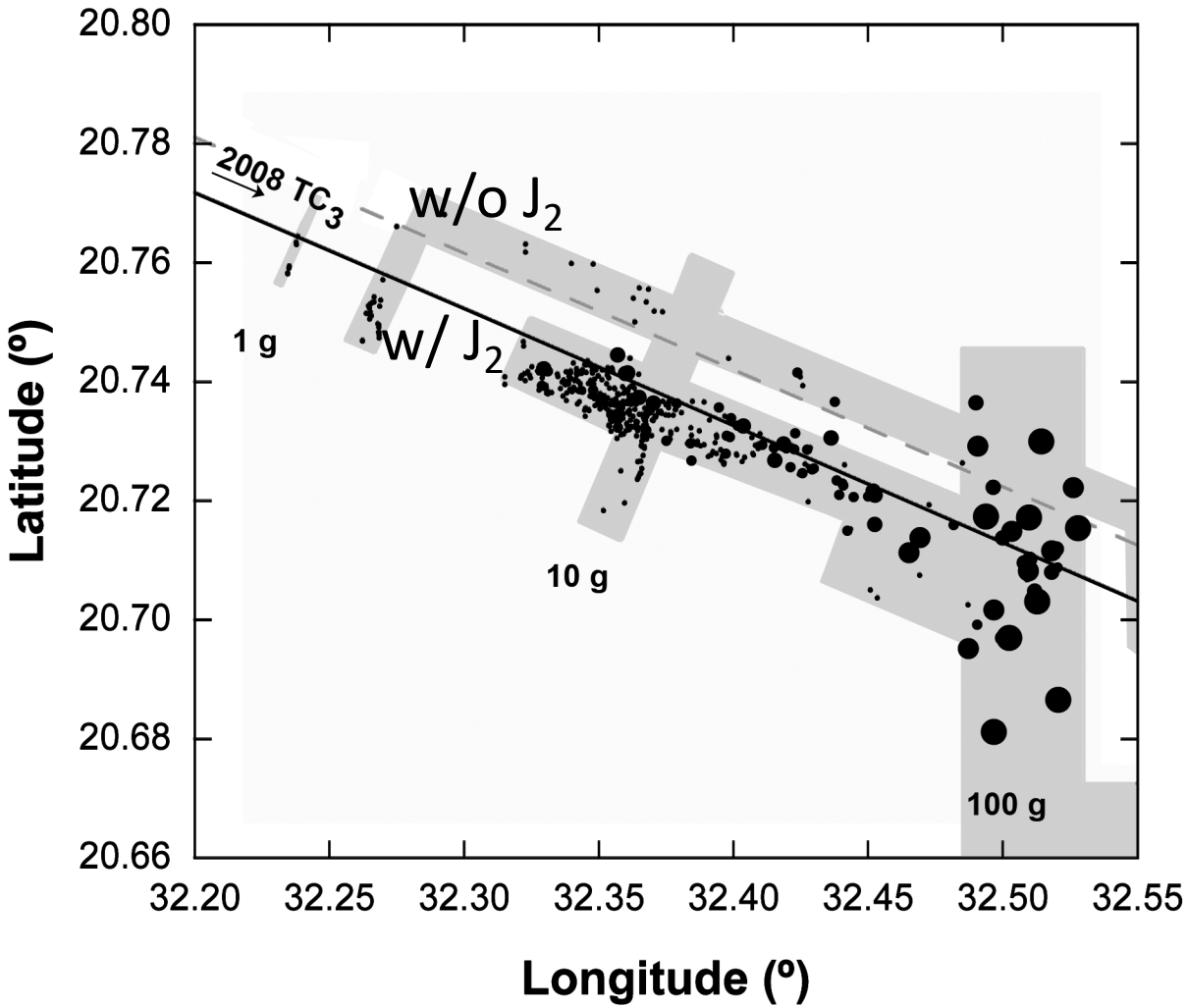
883 observations over 19 h 05 min
1 h to impact
Impact probability 100%



Recovery of meteorites

Jenniskens et al. recovered 600 meteorites for a total mass 10.7 kg.

Sensitivity to geopotential

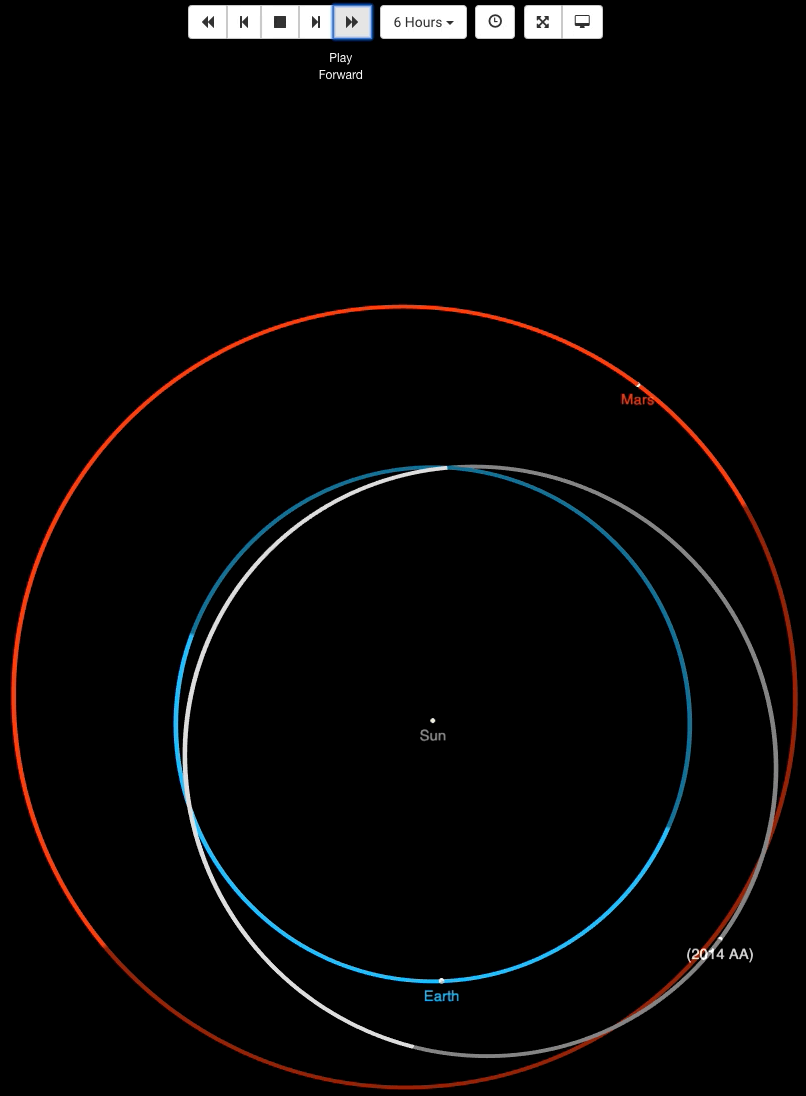


J_2

- 2 km along-track
- 1 km cross-track

Non-zonal and higher order terms:

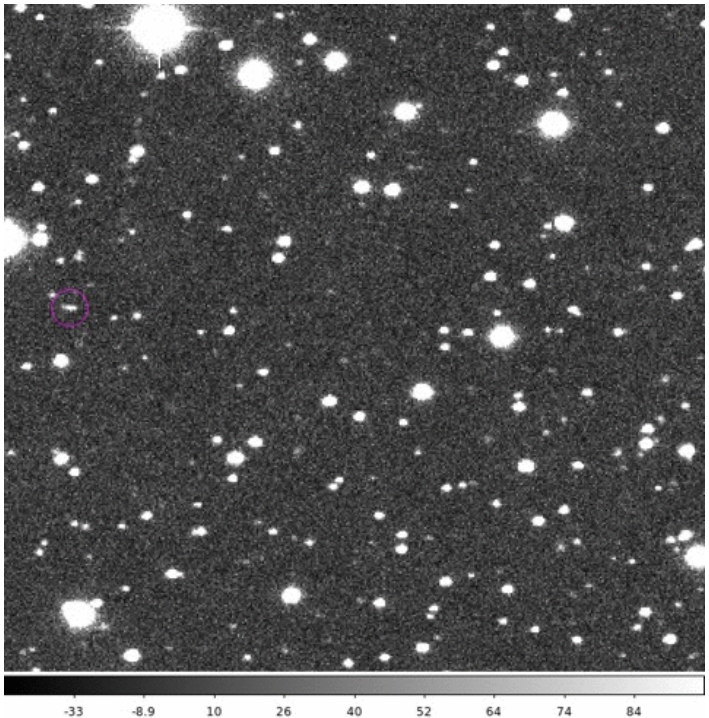
- 17 m along-track
- 3 m cross-track



2014 AA

Jan. 2, 2014

Discovery



Size ~5 m

R. Kowalski, Catalina Sky Survey

20 h before impact

3 observations over 28 min

Follow-up by Kowalski:
4 more observations
69 minutes

Announced by MPC after the impact

The NEO Confirmation Page

Please ensure you are familiar with the notes at the bottom of this page.

Problems? Comments?

Get ephemerides | Reset form

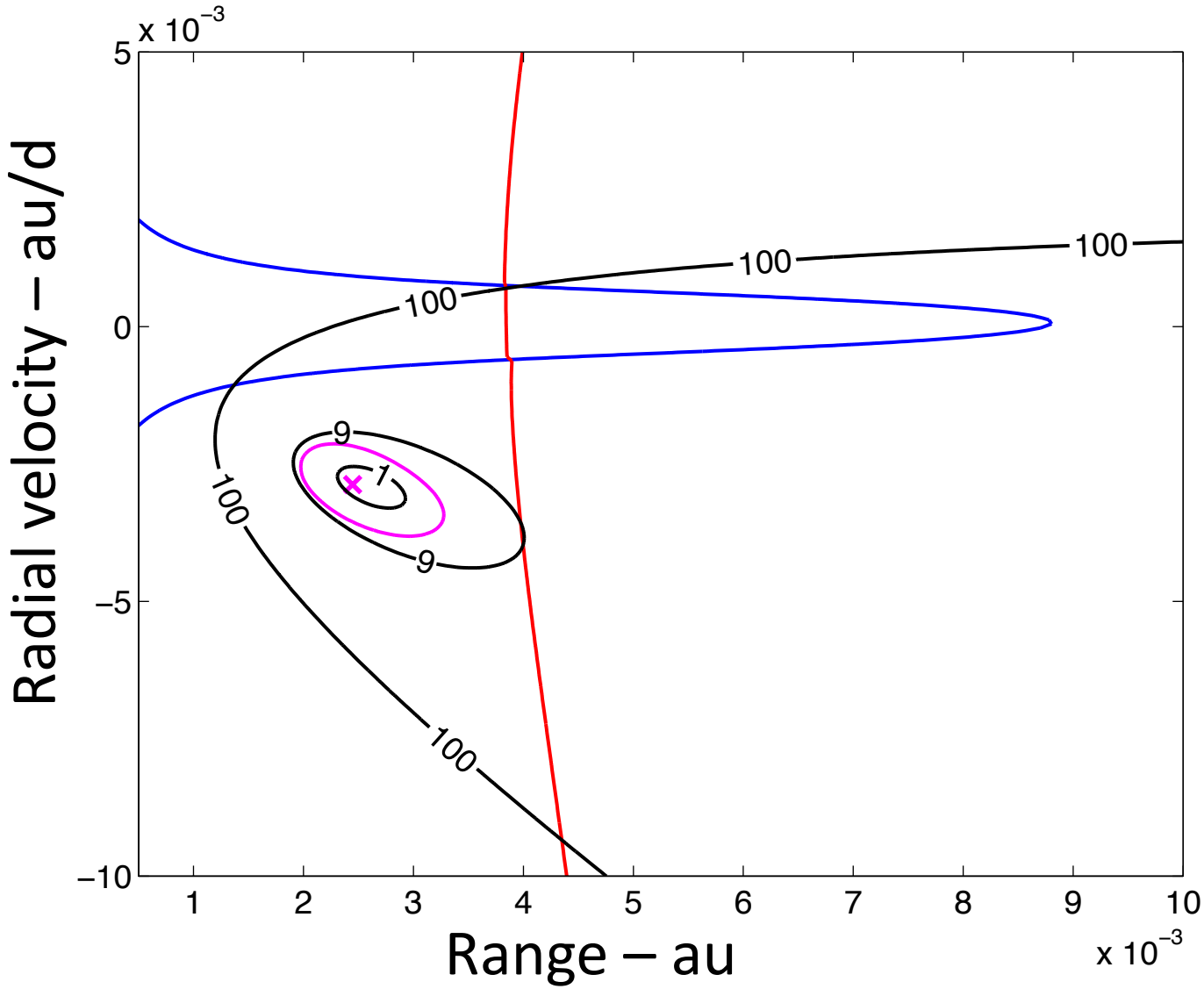
Select object(s) from the current list of objects needing confirmation (NEO desirability score, discovery date, rough current position and magnitude last observed):

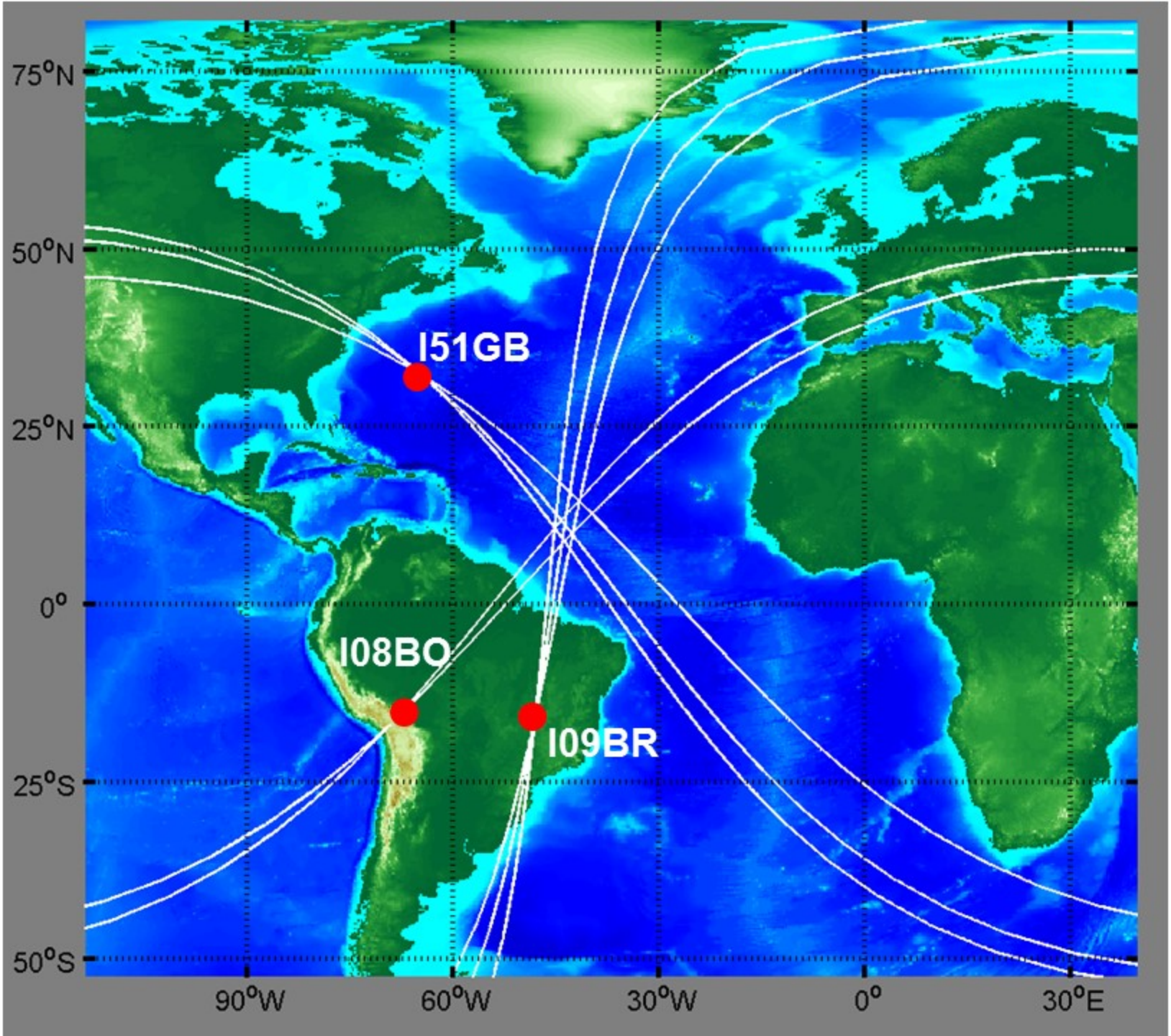
All objects with V = -30 to 30, with Decl. between -90 ° and +90 °, with an NEO desirability score of 0 % to 100 %

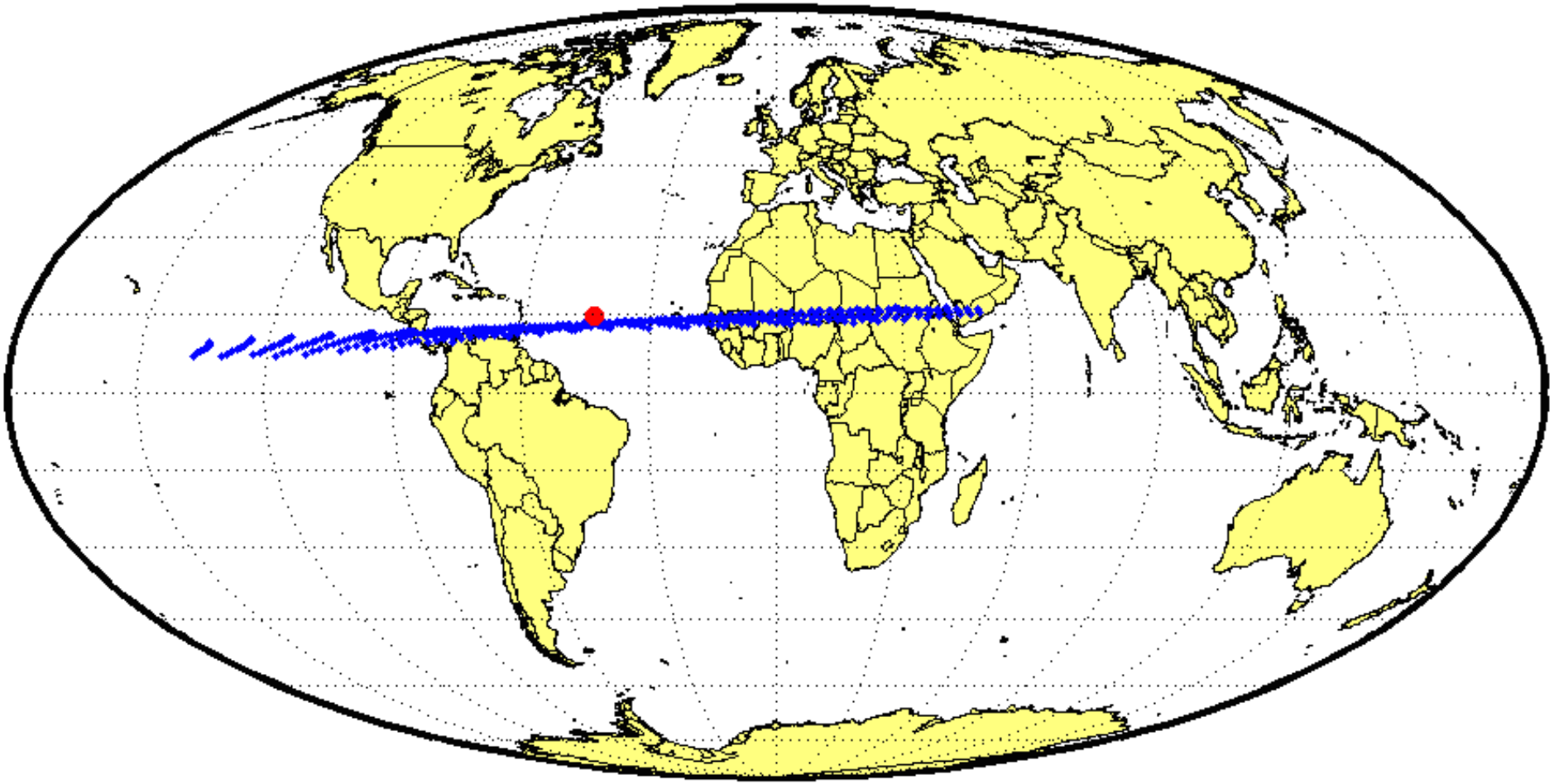
or just the objects selected below: Deselect All | Select All

Temp Desig	Score	Discovery	R.A.	Decl.	V	Updated	Note	NObs	Arc	H	Not Seen/dys
P10NVPC	94	2019 05 19.4	12 58.0	+39 02	21.0	Added May 19.65 UT		4	0.04	12.5	1.527
N00etpw	100	2019 05 16.5	12 41.2	+23 39	20.1	Updated May 20.96 UT		9	4.48	21.6	0.051
C0MVGG2	100	2019 05 15.3	17 22.6	-13 12	19.8	Updated May 17.47 UT		17	1.99	24.6	3.673
C0MWC12	61	2019 05 15.4	20 30.7	+01 54	20.4	Updated May 16.49 UT		19	1.09	16.9	4.524
C0MVNR2	91	2019 05 15.4	15 23.7	+03 02	19.5	Updated May 19.56 UT		22	1.94	24.1	3.695
C0MUJZ2	100	2019 05 15.3	15 48.8	-16 31	20.3	Updated May 16.92 UT		20	1.59	22.7	4.089
ZTF0383	91	2019 05 14.4	03 02.3	+32 06	30.8	Updated May 18.95 UT		21	1.94	24.6	5.653
C0MLYW2	70	2019 05 14.3	15 03.4	-01 14	21.4	Updated May 15.54 UT		19	0.96	22.2	5.751
C0MJVF2	89	2019 05 14.2	15 18.4	-21 47	21.1	Updated May 19.57 UT		25	2.69	24.2	4.060
JA0048	82	2019 04 05.1	12 59.5	-05 57	22.9	Updated May 14.30 UT		6	2.07	6.8	43.808
C0MJAL2	86	2019 05 14.2	06 58.2	+62 07	23.6	Updated May 16.19 UT		21	1.96	27.8	4.815
C0MHM82	10	2019 05 14.2	14 46.9	-18 49	18.8	Updated May 19.91 UT		41	5.66	21.7	1.113
N00et3p	53	2019 05 12.9	12 37.9	+41 14	20.7	Updated May 20.13 UT		25	7.24	18.7	0.884
ZTF0380	91	2019 05 13.4	00 27.2	+60 04	25.1	Updated May 15.39 UT		26	2.05	25.4	5.607

Systematic ranging




75°N
50°N
25°N
0°
25°S
50°S
90°W
60°W
30°W
0°
30°E
I51GB
I08BO
I09BR



11

Scout: NEOCP Hazard Assessment

Introduction | **Data Table** | Object Data | Ephemeris

Data Table

Scout data are about *unconfirmed objects* and all information should therefore be treated as *potentially unreliable*.

The following table contains NEOCP objects analyzed by Scout. Because of the generally short observation arcs and the uncertain quality of the astrometry, the reported impact ratings and scores are meant to identify interesting objects rather than provide a rigorous probability assessment.

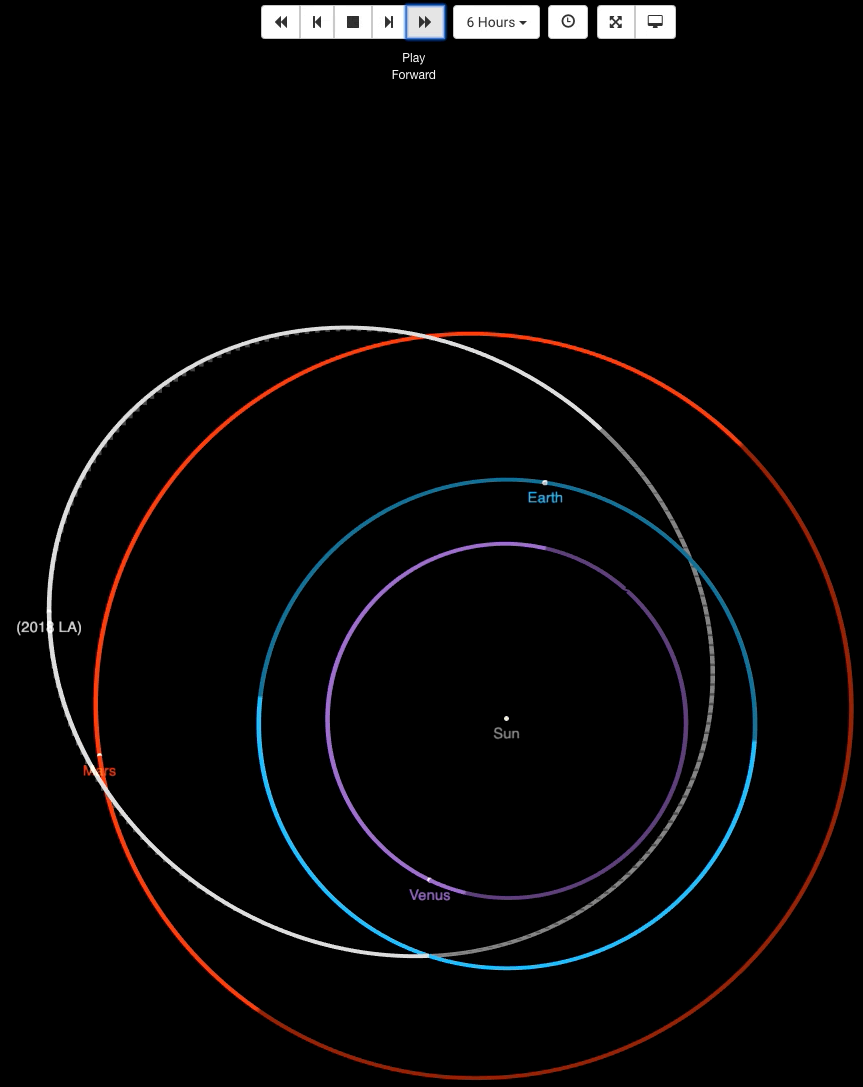
Table Filter: Enter desired filter parameter values then press the "Apply Filter" button.

NEO Score (min)			V-mag (range)			RA (range)		
POS Unc. (range)			Elong. (min)			Dec (range)		
POS Unc.+1 (range)			Rate (max)			Apply Filter	Reset	

Showing 1 to 69 of 69 entries

Search: Search object

Object	#obs	Arc (h)	RMS	H	Impact Rating	MOID (au)	CA Dist. (LD)	V_{inf} (km/s)	PHA	NEO	NEO > 1km	Geo.	IEO	$T_J < 3$	Last Update (UTC)	RA (hh:mm)	Dec. (deg.)	Elong (deg.
ZTF01Ym	6	1.18	0.31	25.2	1	0.01	6.2	16.0	0	100	0	0	0	45	2018-09-28 18:12	02:12	-39	13
P20Jyx5	3	0.59	0.14	26.3	1	0.006	11	10.9	0	100	0	0	0	36	2018-10-04 16:01	02:47	+13	14
P20Jril	3	0.84	0.22	18.9	1	0.4			0	57	9	0	0	61	2018-10-02 18:06	00:40	+06	17
ZSA598F	4	0.41	0.34	26.8	0	0.01	5.2	10.4	0	100	0	0	0	53	2018-09-30 09:19	03:49	+52	11
ZSA3500	3	0.41	0.37	25.9	0	0.06	24		0	100	0	0	0	43	2018-09-30 07:58	23:12	+17	15
A108U34	4	0.72	0.21	27.9	0	0.0005	0.29	9.6	0	100	0	1	0	51	2018-10-01 13:34	08:53	+13	60
A108Z7p	4	0.72	0.28	27.4	0	0.007	2.7	11.1	0	100	0	0	0	49	2018-10-03 13:00	02:09	-39	13
ZSA1411	8	1.65	0.78	27.6	0	0.009	3.4	16.1	0	100	0	0	0	60	2018-09-30 11:00	09:00	-43	62
ZSA4C92	4	0.41	0.42	29.8	0	0.001	0.59	19.7	0	100	0	0	0	61	2018-09-30 08:49	11:47	-00	14
P20Jurc	3	0.56	0.00	26.7	0	0.01	5.8	21.9	0	97	0	0	0	46	2018-10-03 21:26	00:19	-11	16
P20Jri9	3	0.84	0.01	25.9	0	0.05	19	18.3	0	100	0	0	0	43	2018-10-02 17:07	01:46	-21	15
A108Z7t	3	0.48	0.02	24.7	0	0.01	6.3	29.0	0	100	0	0	0	28	2018-10-03 15:32	00:28	-18	15
A108WON	4	0.77	0.45	23.3	0	0.02	14	14.5	0	100	0	0	0	56	2018-10-02 15:47	02:56	33	13



2018 LA

Jun. 2, 2018

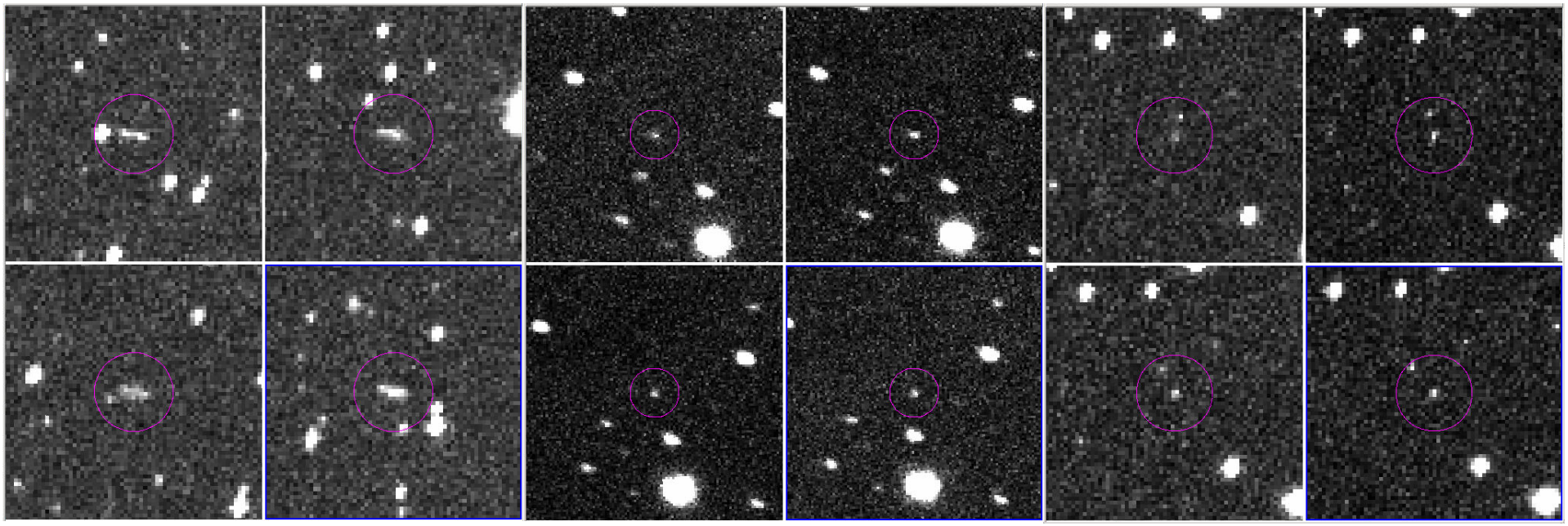
Text Message
Yesterday 1:32 PM

1 of 2
FRM:JPL Scout System
SUBJ:Scout: ZLAF9B2
MSG:IP = 5%, CA_DIST=6.1 RE,
URL = http://cneos.jpl.nasa.gov/scout/#/object/ZLAF9B2

MÖVENPICK
So kann Eis sein.
afri cola
MISSION JUNO

All my friends are dead

Based on 11 observations from Catalina Sky Survey



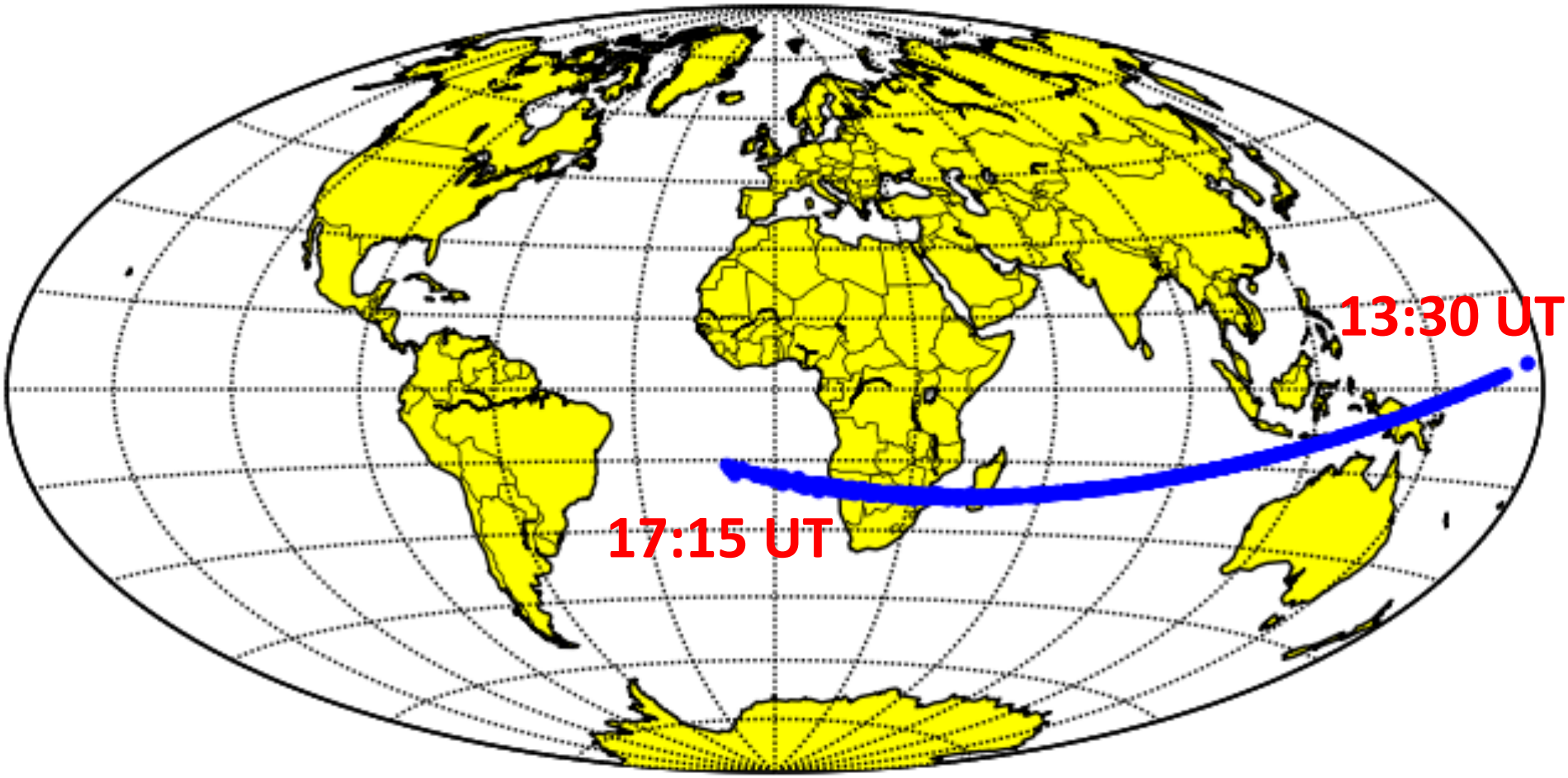
G96
08:14 to 08:37 UT

I52
09:33 to 09:37 UT

G96
09:39 to 09:40 UT

8 hours prior

It’s Kowalski!



H between 30.5 and 32.2

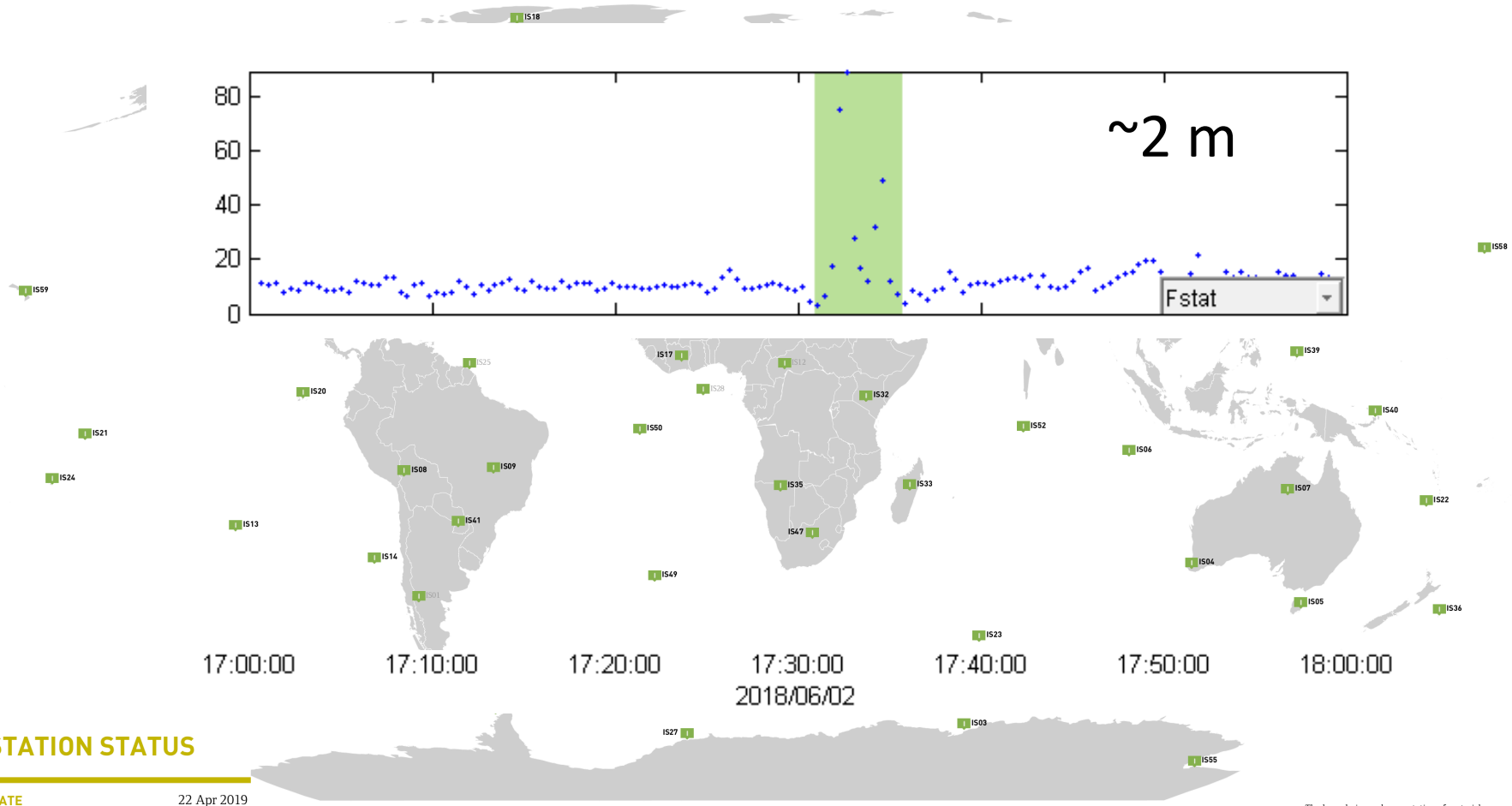
American Meteor Society

INTERNATIONAL MONITORING SYSTEM

INFRASOUND NETWORK - CERTIFIED STATIONS AND NON-CERTIFIED STATIONS

22 APRIL 2019

CTBTO PREPARATORY COMMISSION | preparatory commission for the comprehensive nuclear-test-ban treaty organization



STATION STATUS

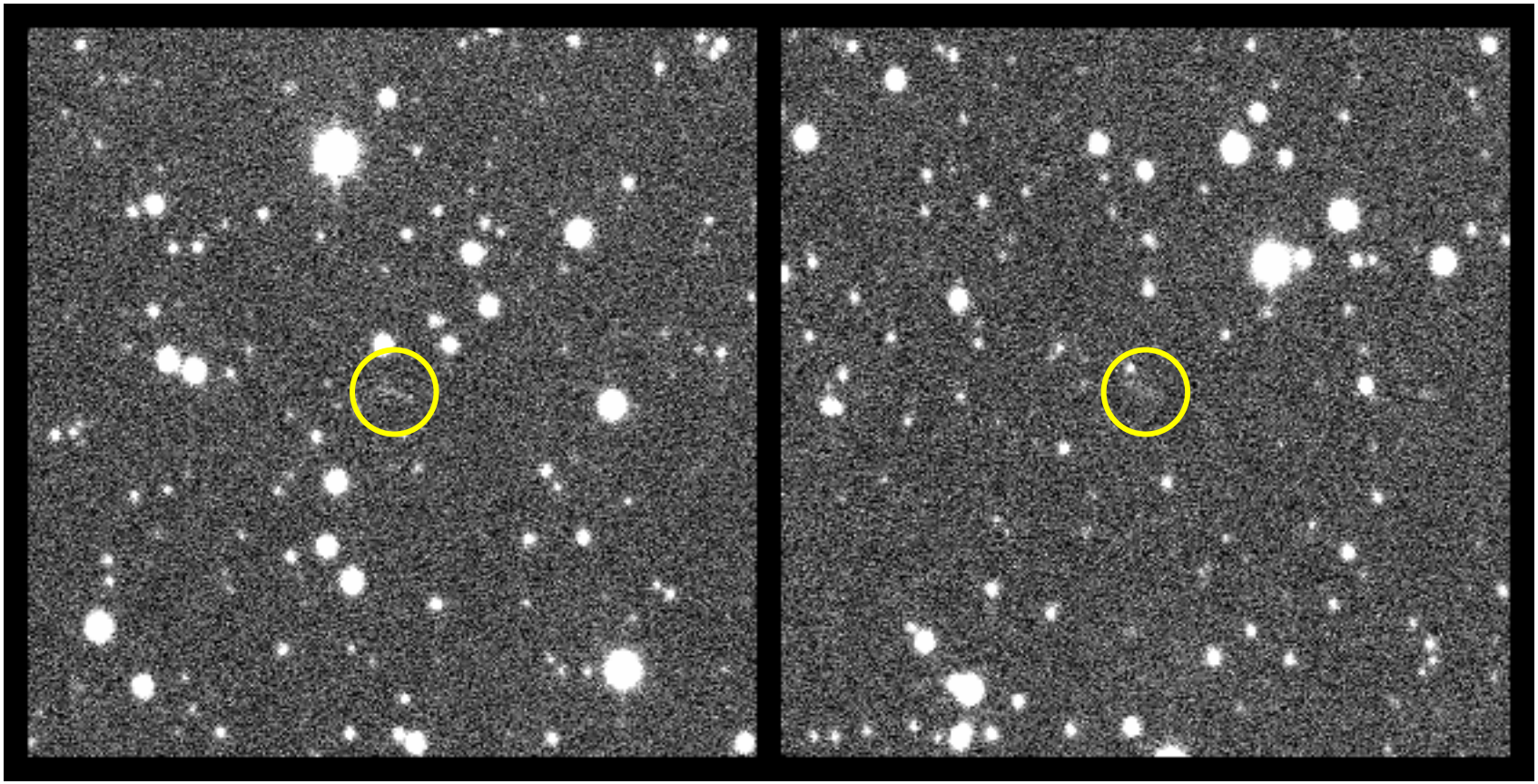
DATE	22 Apr 2019
TOTAL STATIONS	60
PLANNING	7
UNDER CONSTRUCTION	1
INSTALLED	1
CERTIFIED	51

Sp Primary Seismic | SA Auxiliary Seismic | I Infrasound | H Hydroacoustic | R Radionuclide | R+ Radionuclide w/ Noble Gas | L Radionuclide Lab

The boundaries and presentation of material on this map does not imply the expression of any opinion on the part of the Provisional Technical Secretariat concerning the legal status of any country, territory, city or area or its authorities, or concerning the delimitation of its frontiers or boundaries.

WWW.CTBTO.ORG

ATLAS pair



T08

11:49 to 12:01 UT

USG Fireball Report

Energy 0.98 kt

Altitude 28.7 km

Latitude 21.2° S

Longitude 23.3° E

Time 16:44:12 UT

Velocity 17 km/s

Jet Propulsion Laboratory
California Institute of Technology

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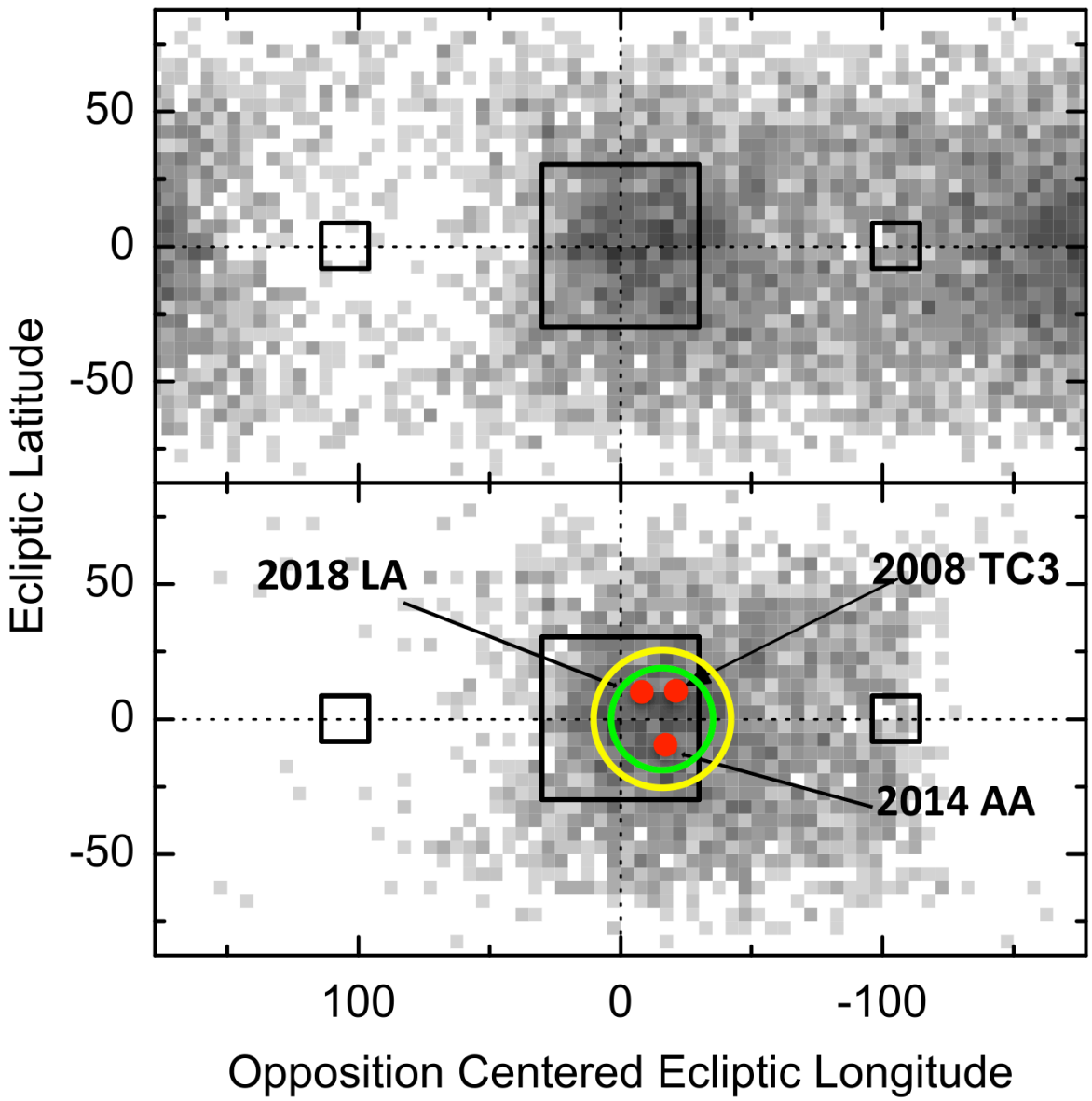
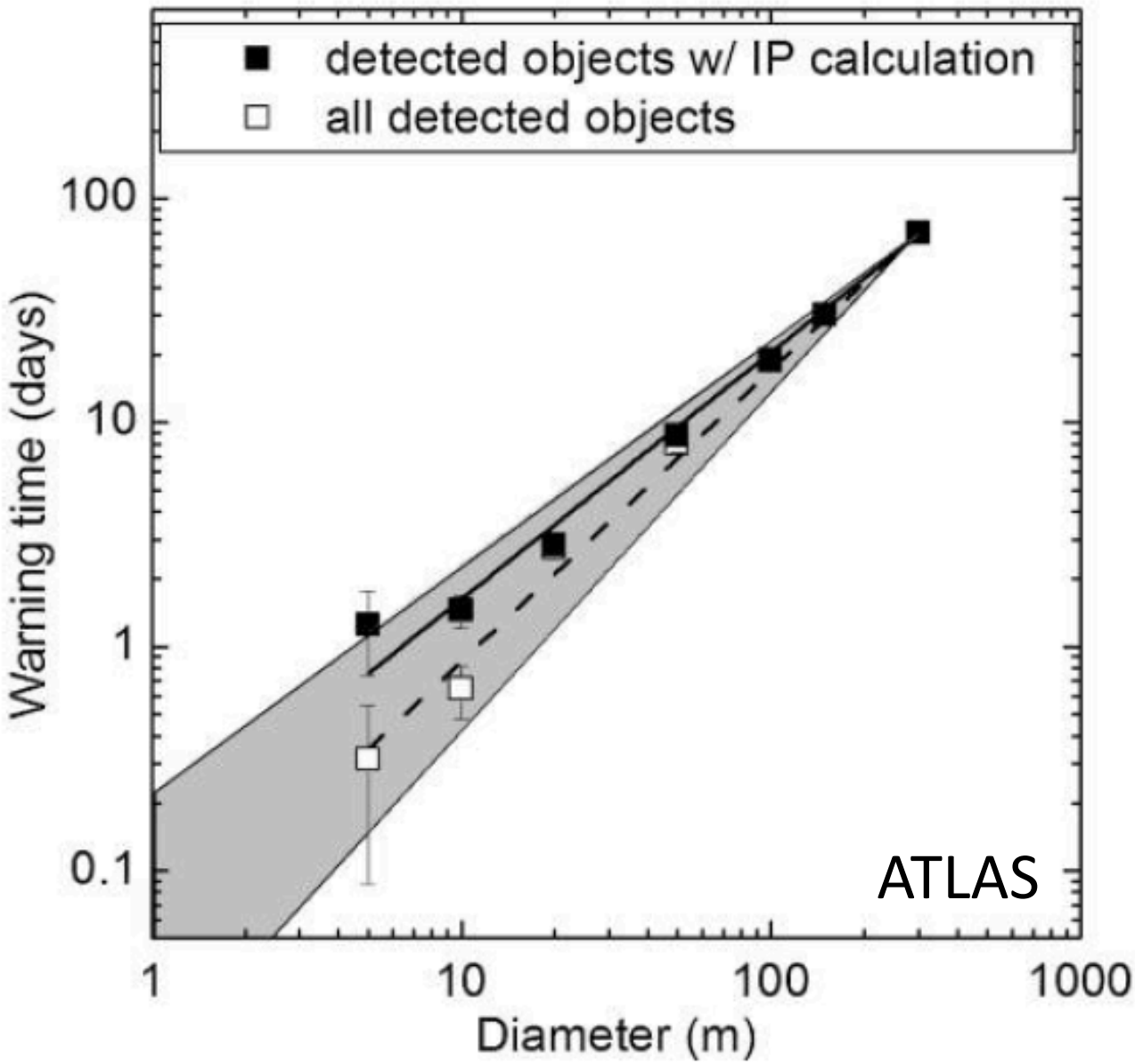
Veres et al. 2009, one day prior to impact

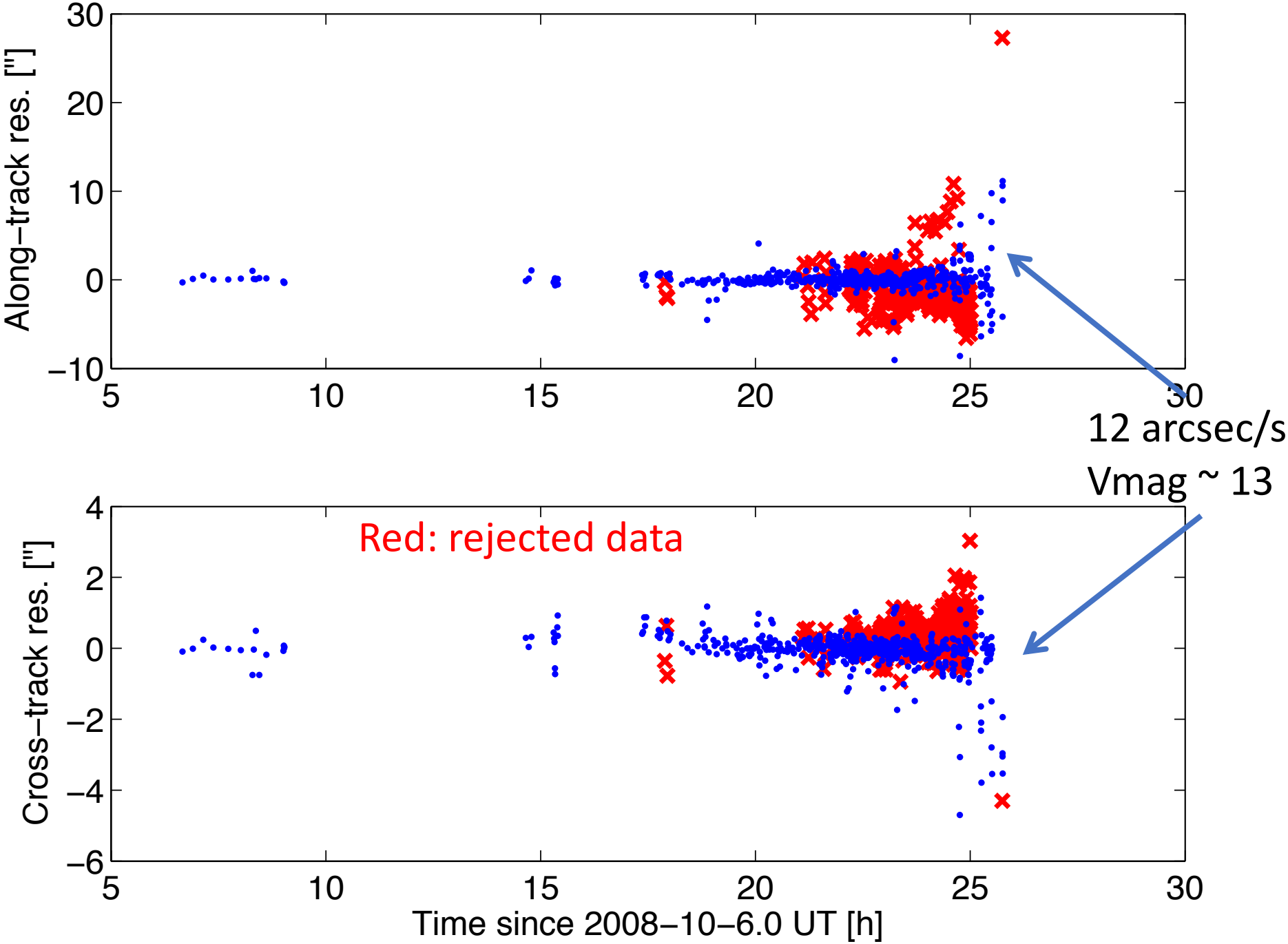


All

V < 22.7
Rate < 12°/day

Veres et al. 2014

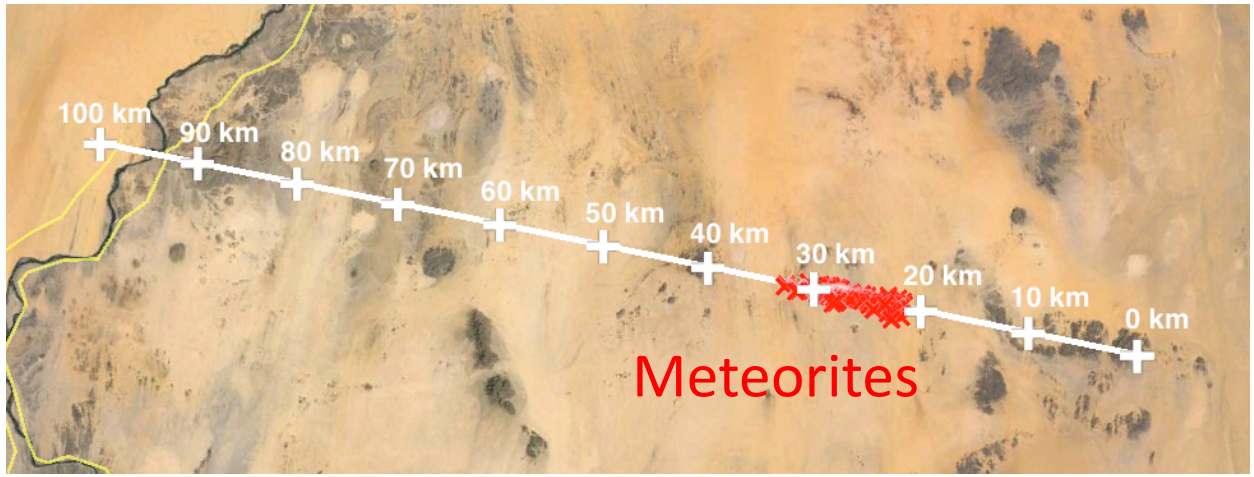



Along−track res. ["]
Cross−track res. ["]
Time since 2008−10−6.0 UT [h]
Red: rejected data
12 arcsec/s
Vmag ~ 13

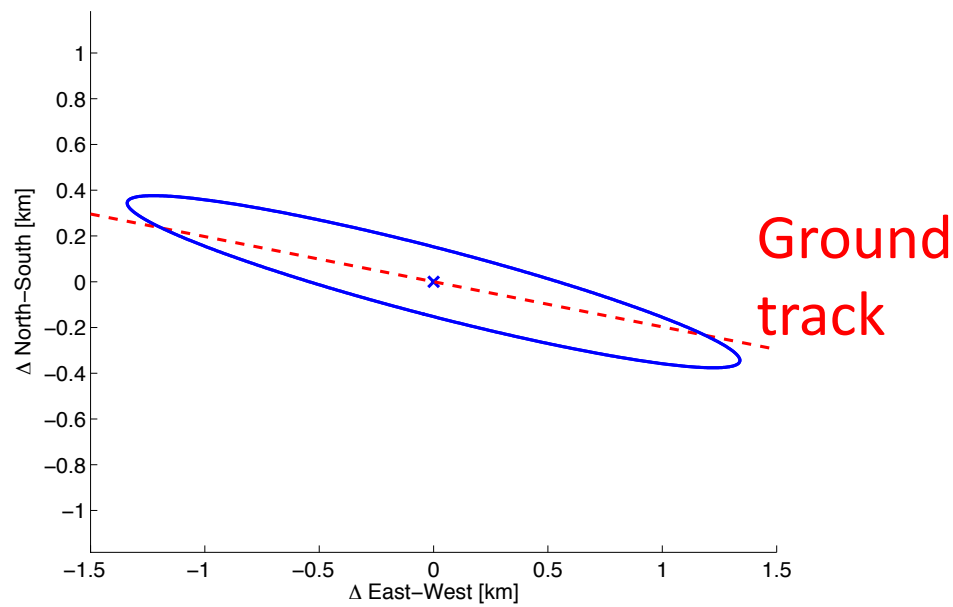
Impact location estimate

Ground track
Entry angle of 21°

h = 100 km
Lat = 21.087°
E Long = 30.538°
Time = 02:45:30.3 UT



3-σ time error of 0.5 s
3-σ error ellipse of 1.4 km × 150 m



Atmospheric drag

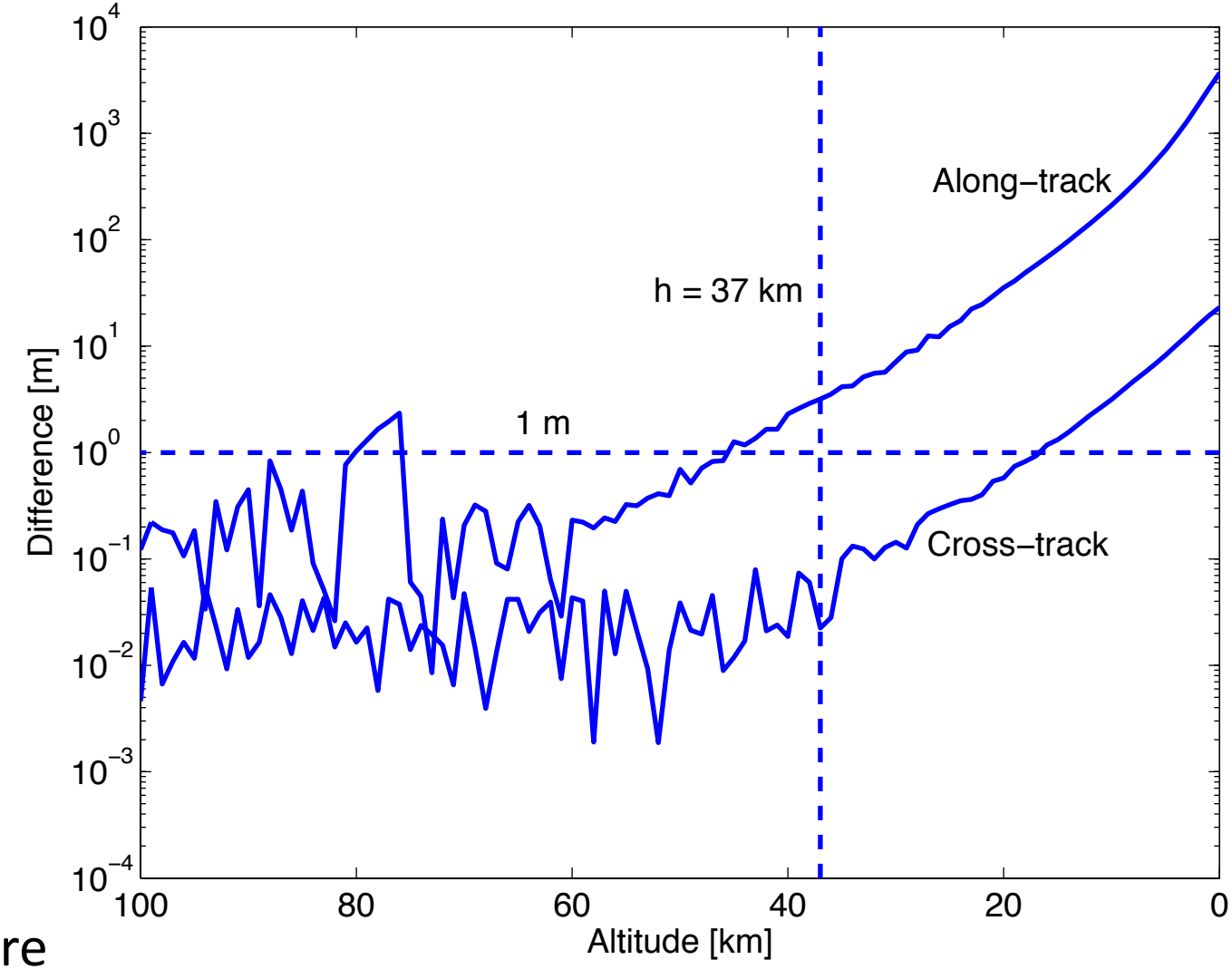
$$a_{drag} = -\frac{1}{2}\rho_{atm} C_D \frac{A}{M} v^2$$

Drag coefficient
$C_D = 1.8$

Cross section
$A = 13.2\ m^2$

Mass
$M = 83\ t$

COSPAR 2012
reference atmosphere



Negligible effects

	Error
Numerical noise	~ 3 m
Earth rotation model	~ 30 cm
Solar radiation pressure	< 1 m
Yarkovsky effect	< 1 m
General relativity vs EIH	< 1 m
Additional perturbers	< 1 m
Planetary Ephemerides	< 1 m