Asynchronous Laser Transponder Experiment in Deep Space Using MESSENGER's Mercury Laser Altimeter

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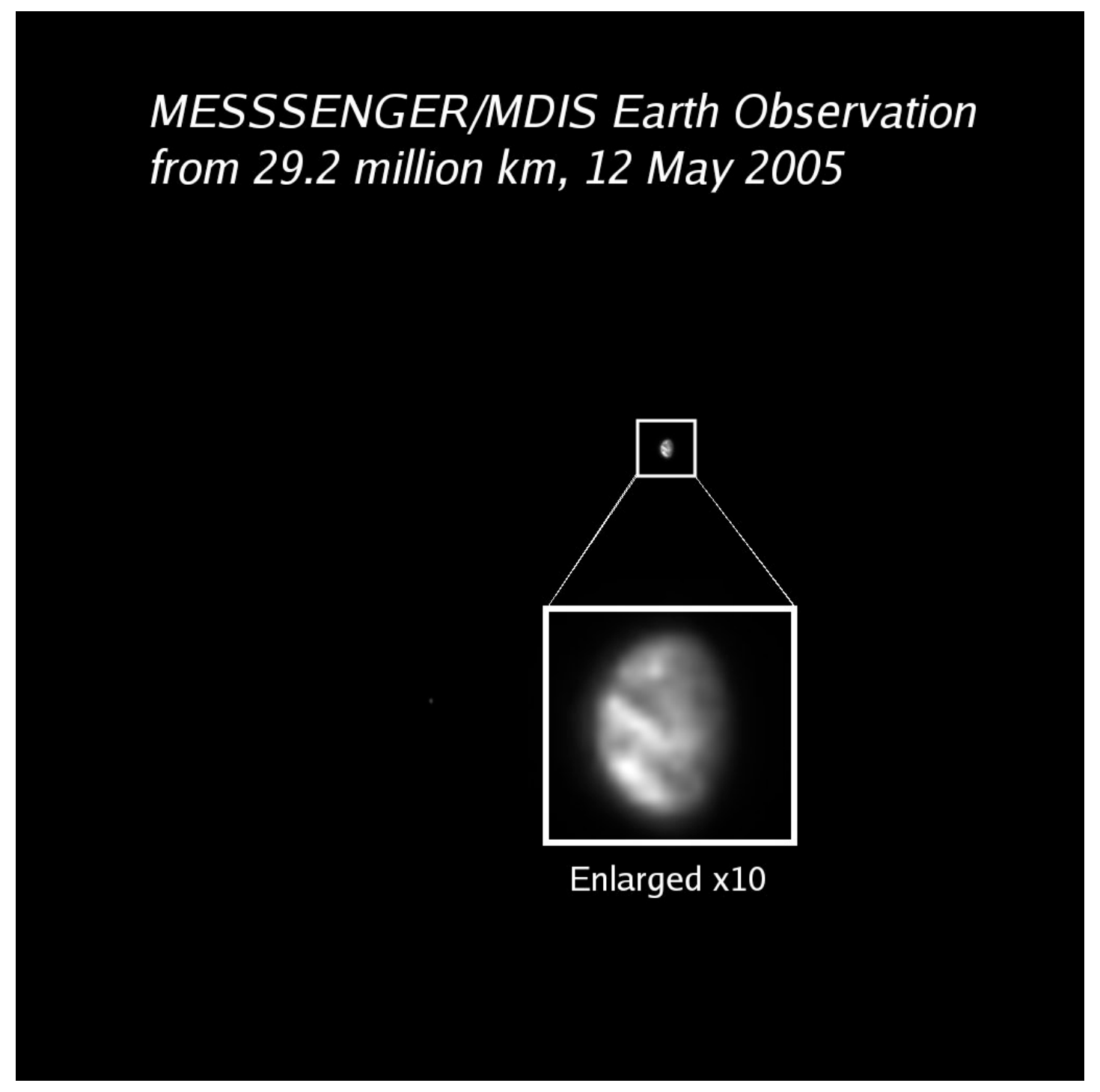
Abstract:

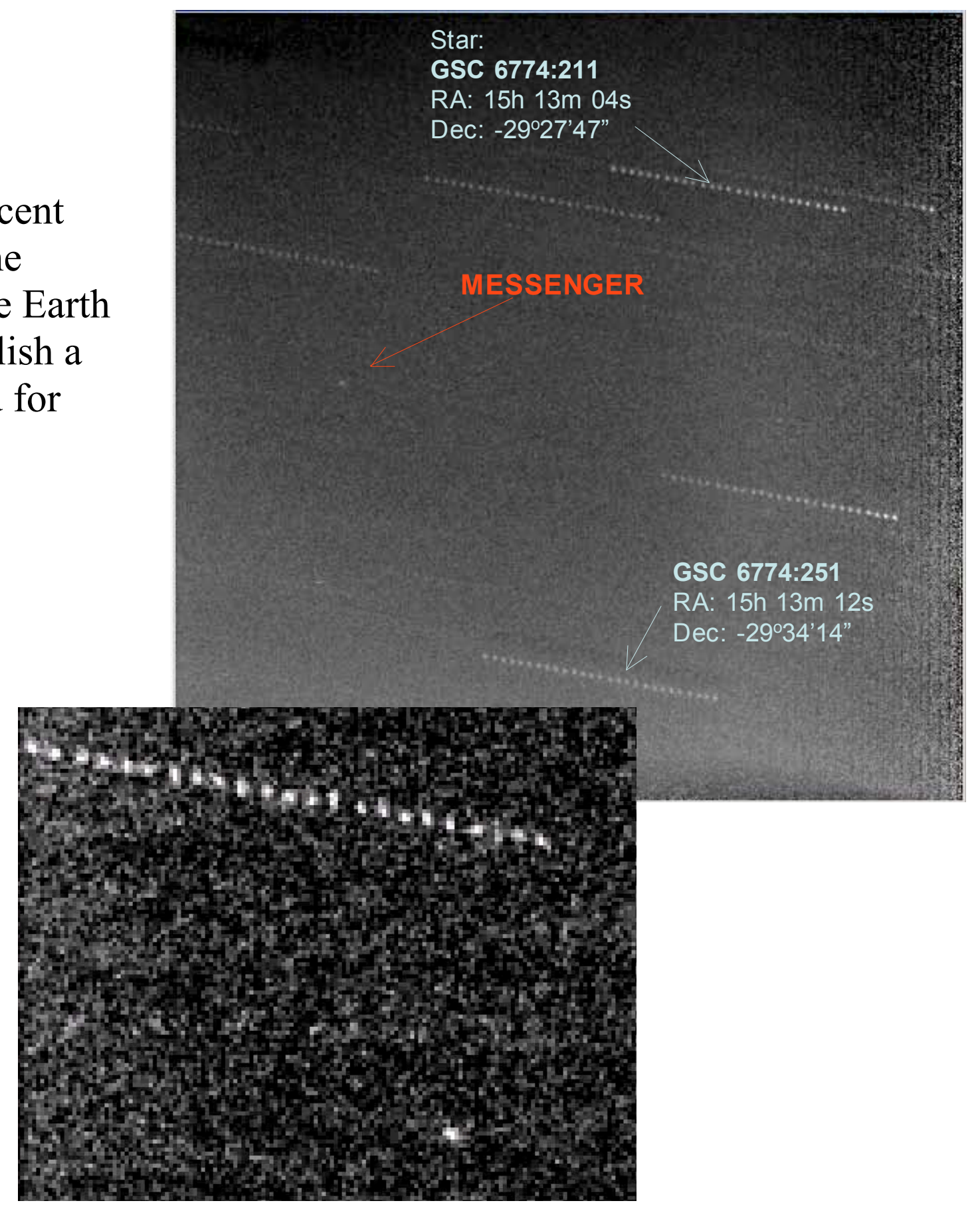
The Mercury Laser Altimeter (MLA) aboard the MErcury Surface, Space Environment, GEochemistry, and Ranging (MESSENGER) spacecraft ranged to Earth as part of its in-flight calibration activities, while NASA's Goddard Geophysical Astronomical Observatory (GGAO) fired laser pulses at MLA. On two separate afternoons, while MESSENGER was visible above the horizon at a distance of 24 million km, trains of 16 and 25 consecutive pulses were detected at GGAO with inter-arrival times matching those transmitted by MLA, while for 30 minutes on one afternoon at least 90 pulses from GGAO were detected by MLA. A linear fit to the MLA pulse time-of-flight revealed a 4.154 km/s Doppler shift in the nominal 8-Hz firing rate, with the majority of pulse centroid times fit to within 300 ps, and for the extended but weaker detections at MESSENGER, the majority could be fit by a quadratic curve within 2.5 ns. The ability to make such precise measurements, together with MESSENGER's stable on-board clock, allows a solution with formal covariances for two-way range, range-rate, and acceleration, as well as clock parameters. We discuss the implications of this calibration experiment for the measurement of orbital and geodetic parameters via asynchronous laser ranging.

Sound bite: 20 cm ranging at 0.2 AU!

1) Introduction:

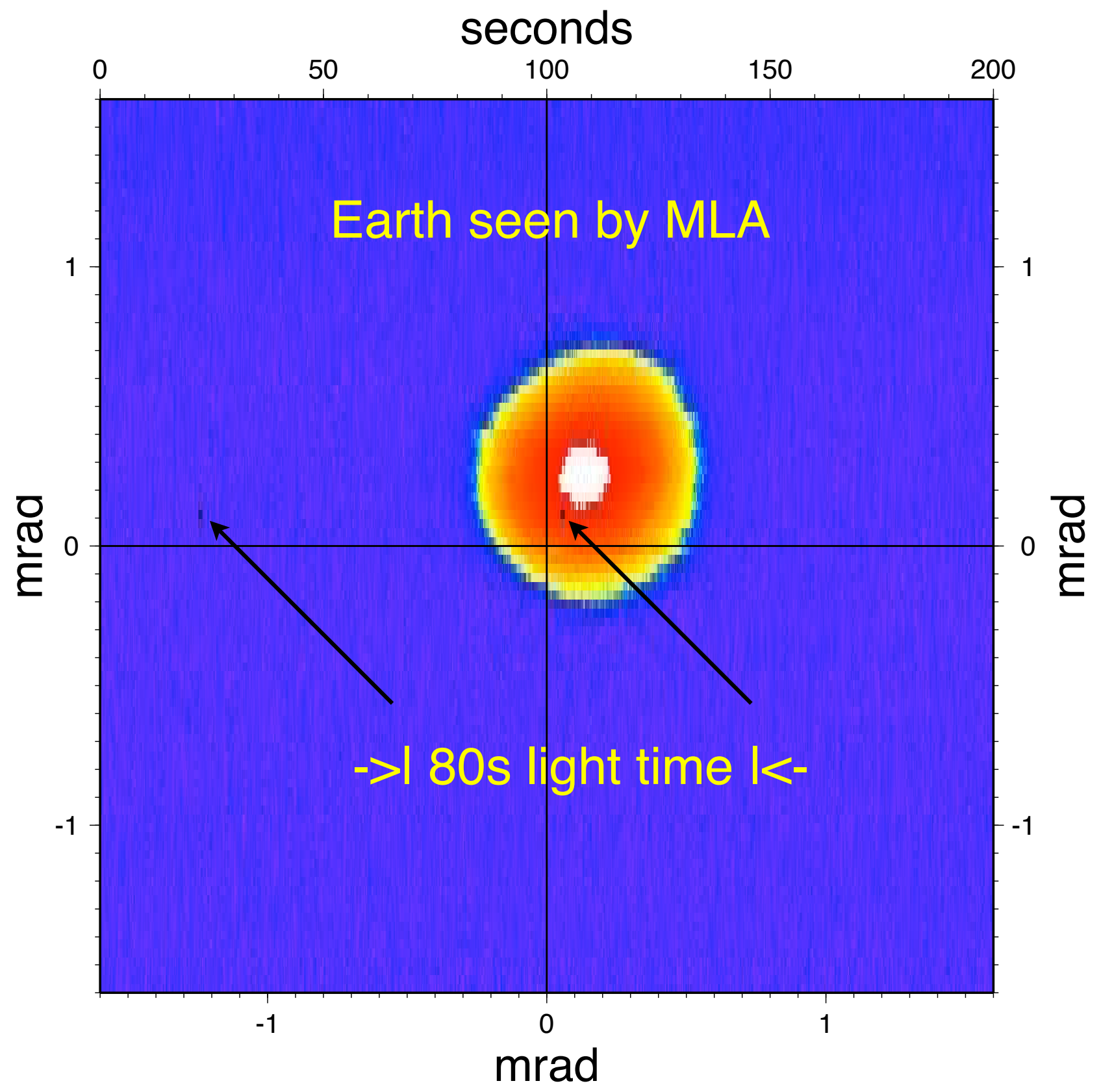
The MESSENGER spacecraft is seen here as a tiny bright spot during its recent Earth flyby mission phase. Three months earlier, at 200x farther distance, the spacecraft was invisible. Nevertheless, MESSENGER was able to image the Earth and Moon with its MDIS camera. At the same time, MLA was able to establish a two-way laser link with milliwatt-level power and set a new distance record for interplanetary laser ranging.

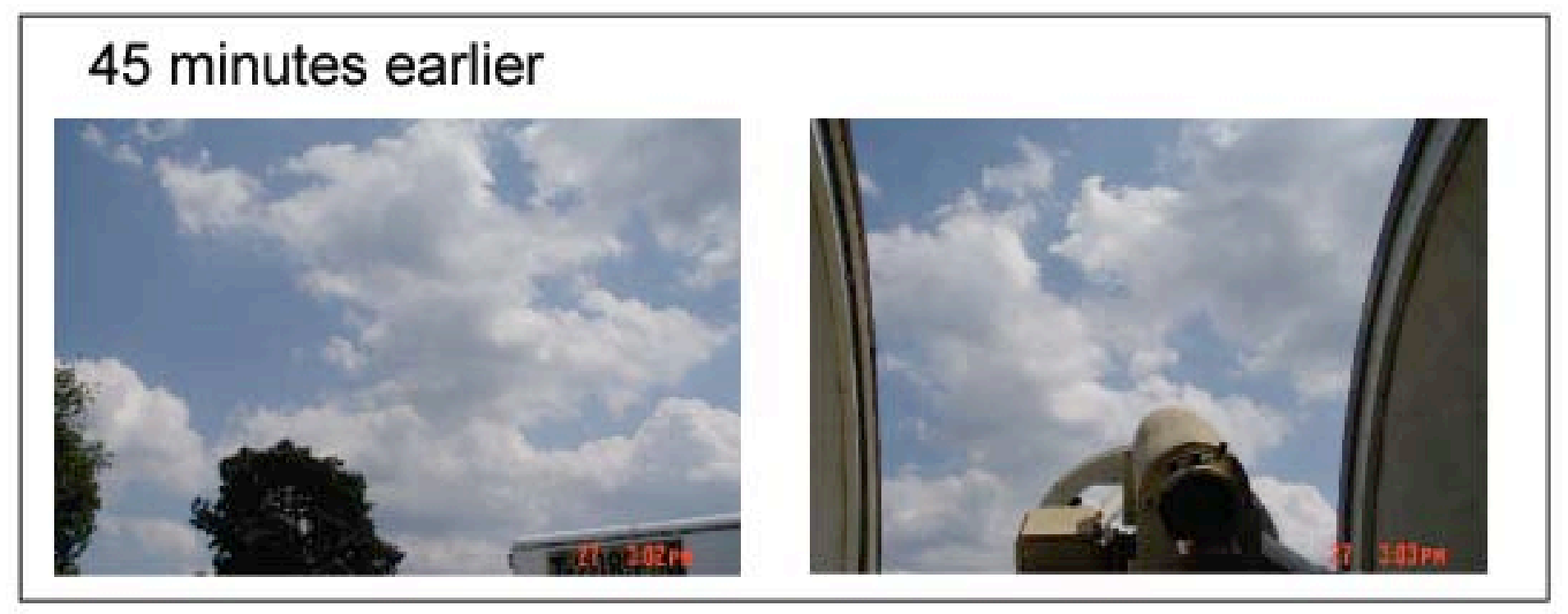


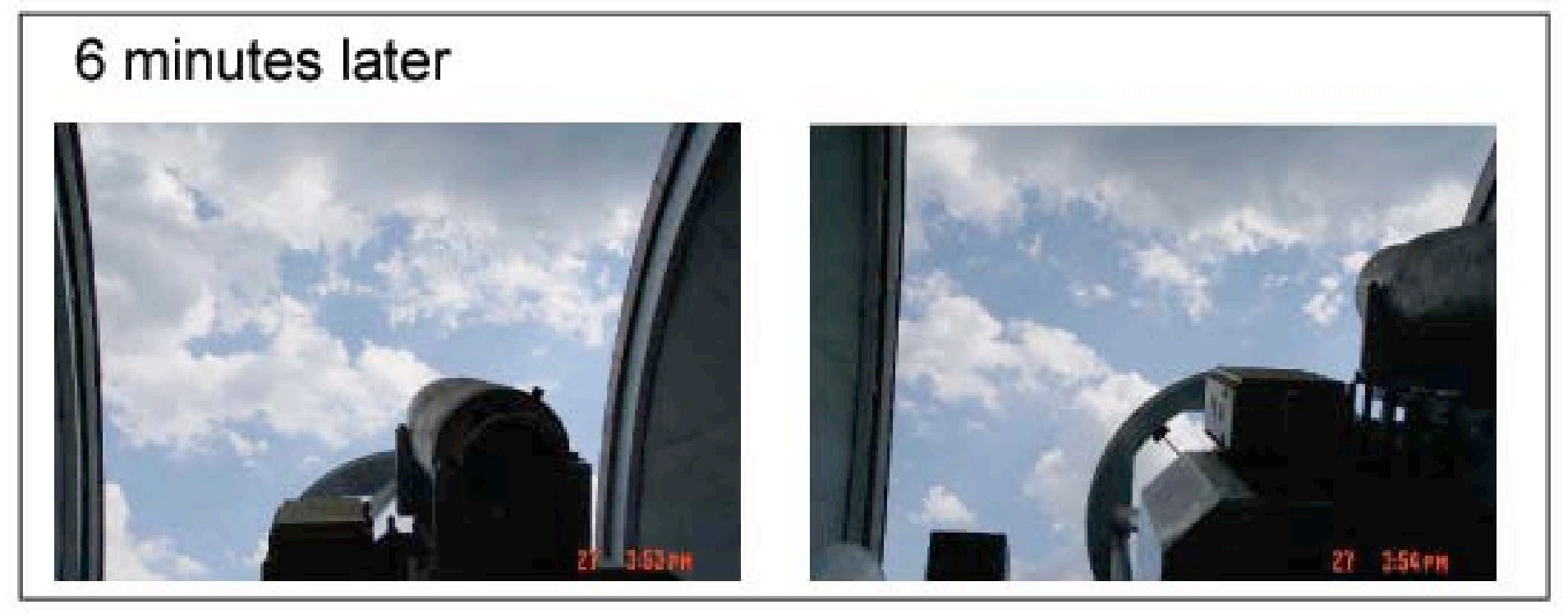


Images of the sunlit MESSENGER spacecraft shortly after the Earth fly-by at 120,000 km distance. MESSENGER appeared as a 17th Visual Magnitude star. The raw images were taken with a 14" Meade LX200GPS telescope and a SBIG ST-9E CCD camera. The image shown above is the sum of 27 raw images, each with 3 seconds exposure time. The spacecraft position solved from these images using Astrometrica software was, Time: August 3, 2005 01:27:08 (UTC), RA: 15h 13m 11.18s, DEC: -29°29'02.8", which agreed with the predicted ephemeris to within 8 arc-seconds.

- David R. Skillman and Xiaoli Sun, NASA GSFC, Code 694

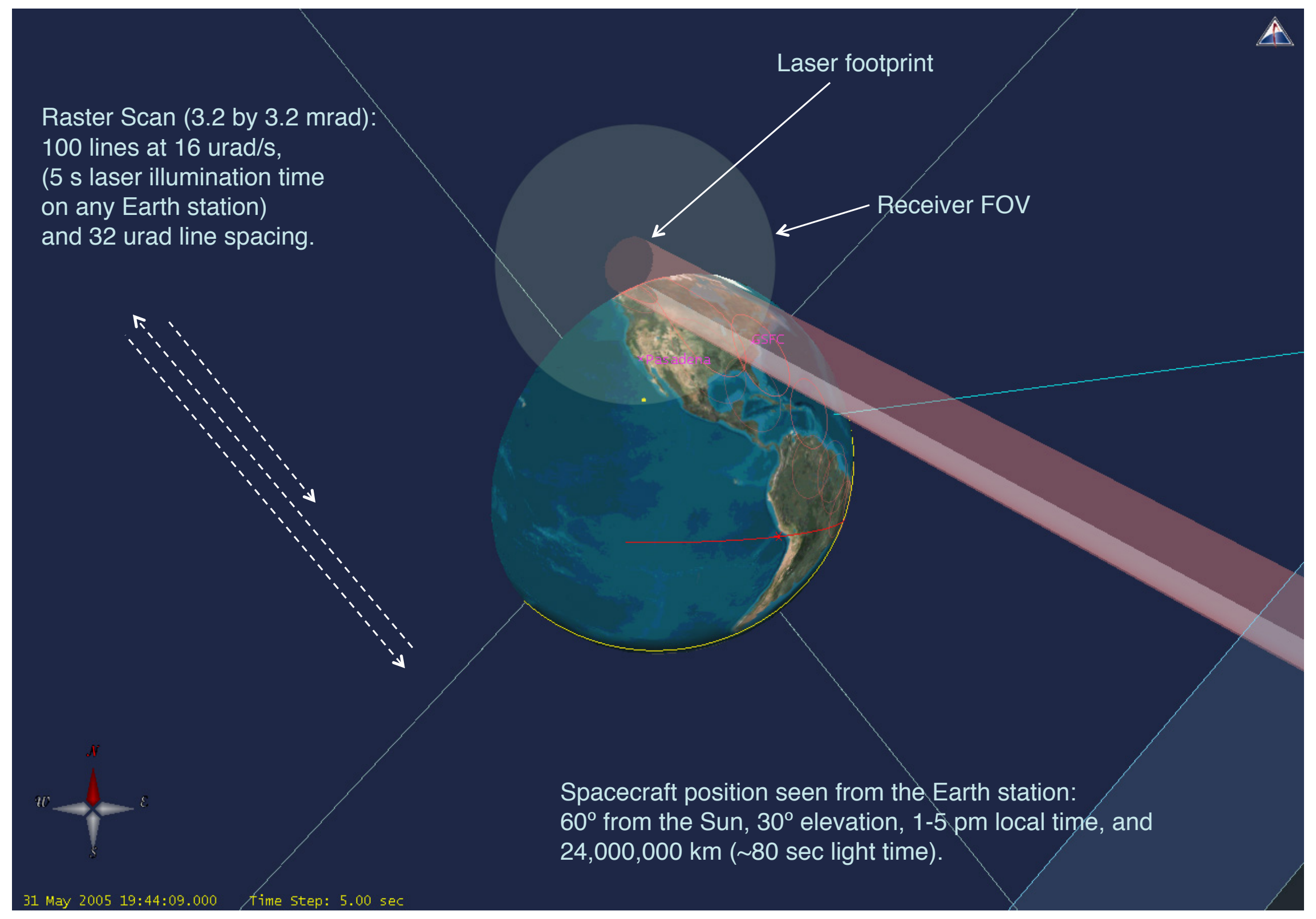



45 minutes earlier


6 minutes later

2) The experiment geometry:

In order to transmit pulses, MESSENGER performed an extended fine raster scan about the nominal position of the GGAO on planet Earth, while the 48" telescope tracked the position of MLA in the sky, seen here on May 27, 2005 prior to and just following receipt of laser pulses. Mid-afternoon clouds obscured the view much of the time that MESSENGER appeared above the horizon. A scan of the Earth showed the position of Earth in the MLA field of view using its detector as a passive radiometer (left). Axes give the angular position of the spacecraft z-axis relative to the predicted position of GGAO, and the duration of the scan across track. Small dark dots show where boresight was pointed at the time pulses were received at Earth, and ~79.9 seconds earlier when the pulses were fired. The receiver field of view is considerably wider than the laser beam, which covered a circle about 1900 km across on Earth and was visible for at most 5 seconds per scan line.



Raster Scan (3.2 by 3.2 mrad):
100 lines at 16 urad/s,
(5 s laser illumination time
on any Earth station)
and 32 urad line spacing.

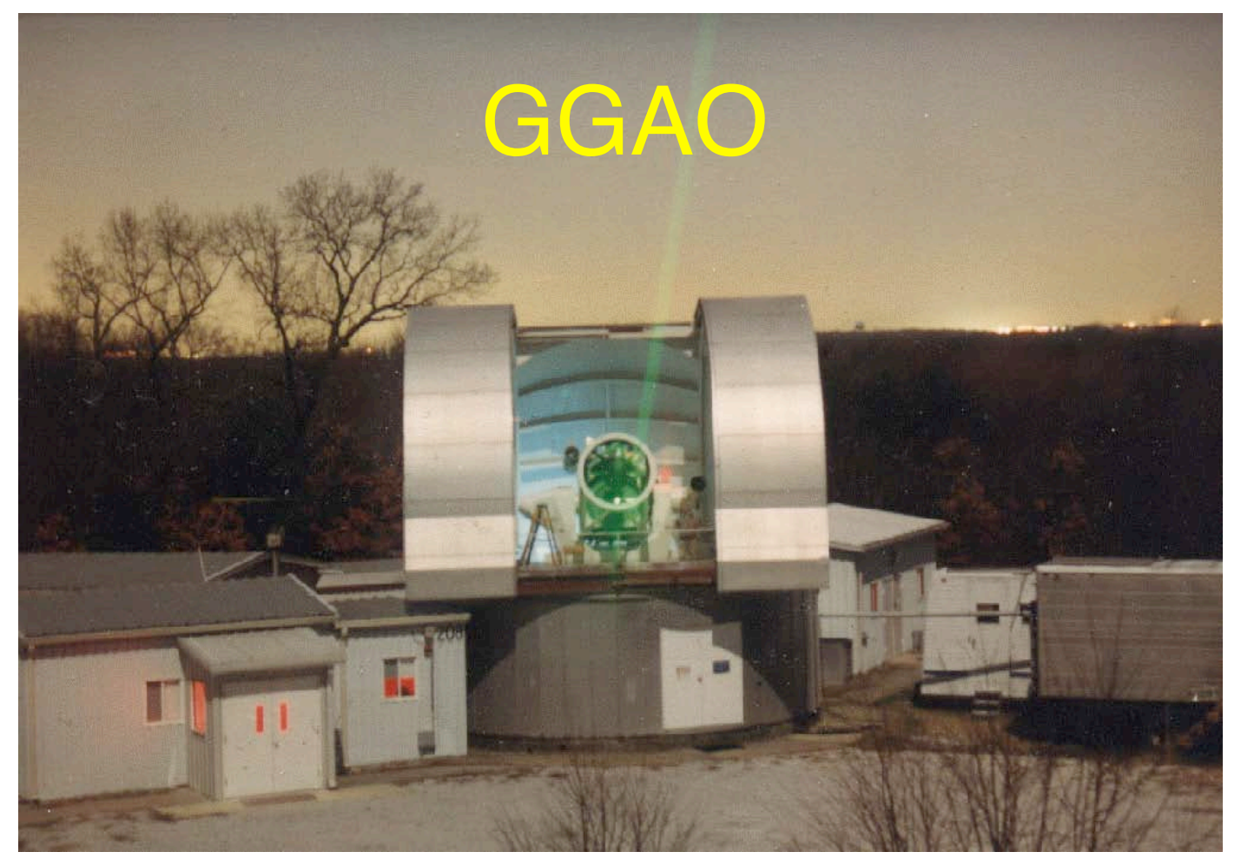
Spacecraft position seen from the Earth station:
60° from the Sun, 30° elevation, 1-5 pm local time, and 24,000,000 km (~80 sec light time).

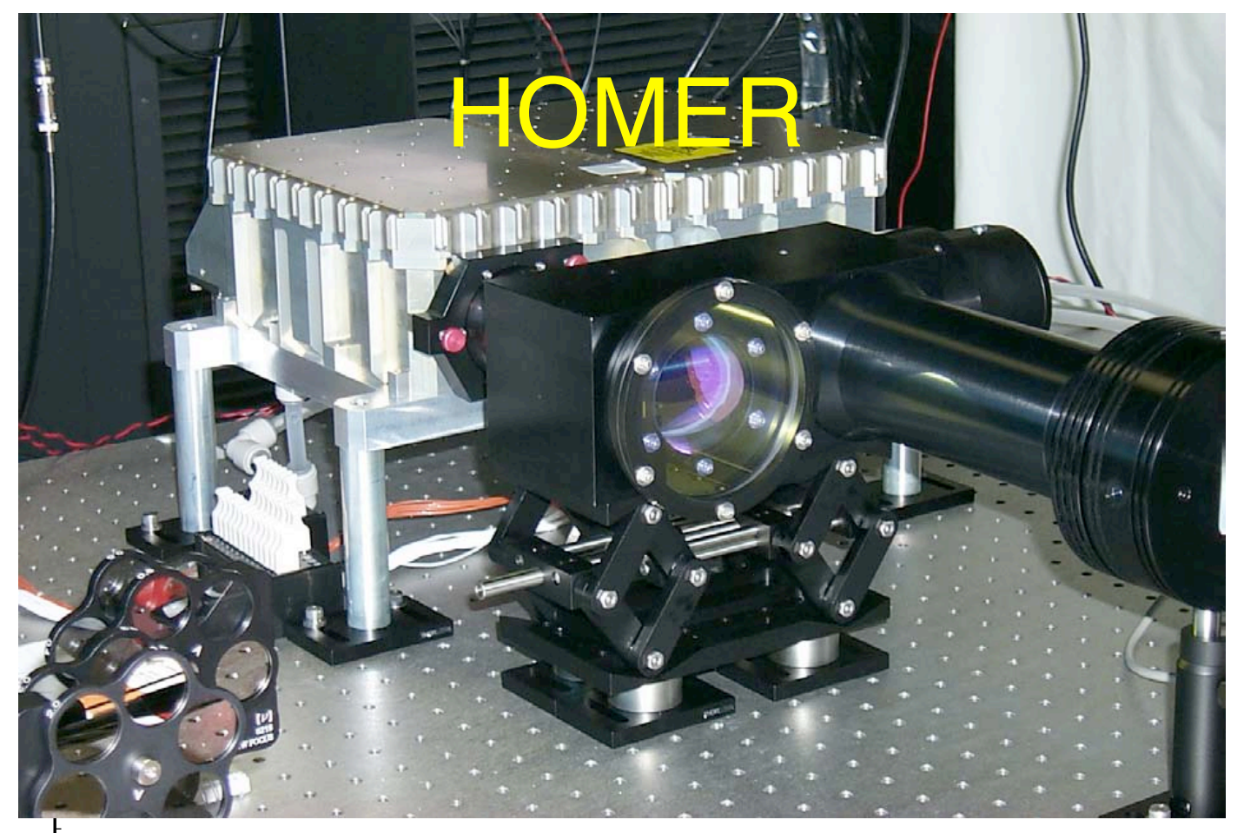
3) Ground station and instrument parameters:

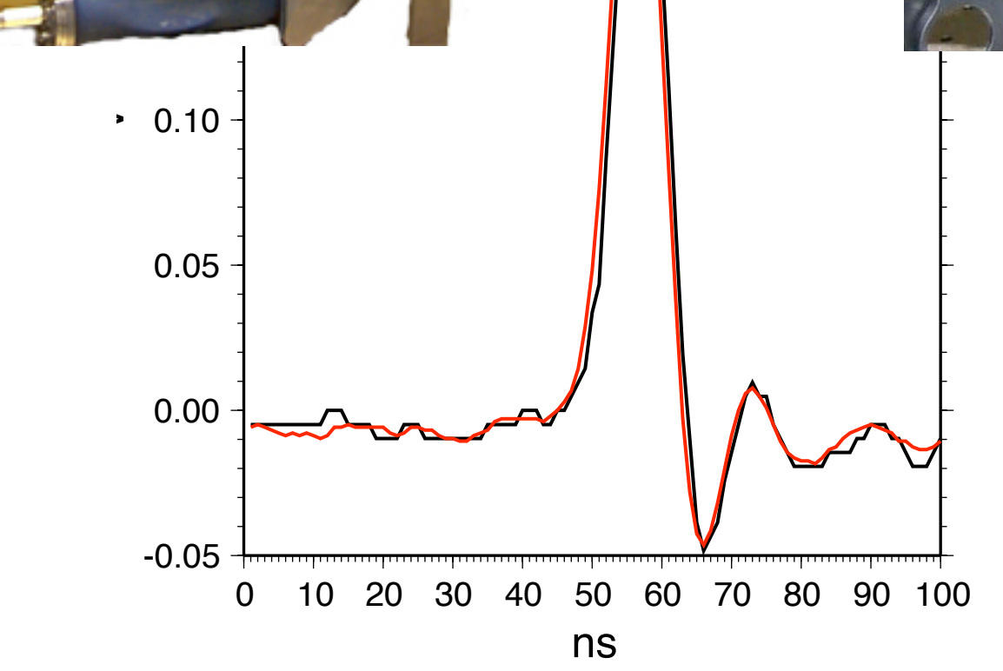
Parameter	GGAO	MLA
Transmitter:		
Wavelength nm	1064	1064
Pulse energy, mJ	14	18
Pulse repetition rate, Hz	240	8
Pulse width, ns	10	6
Beam divergence (FWHM), μrad	55	50
Receiver:		
Telescope diameter, m	1.2	0.23
Detector field of view, μrad	260	400
Alignment		
Transmitter-receiver boresight,μrad	25	50
MLA alignment wrt s/c instrument deck, mrad		3.5

The HOMER[1] laser transmitter (bottom) operated continuously at GGAO (here shown firing at twilight at 532 nm). The MLA transmitter (bottom left, in center of instrument) operated for 5+ hours at a time during scans. Both lasers performed flawlessly. The large ground telescope provided adequate downlink margin while the MLA optics (four corner barrels) had a much smaller aperture for uplink.

MLA





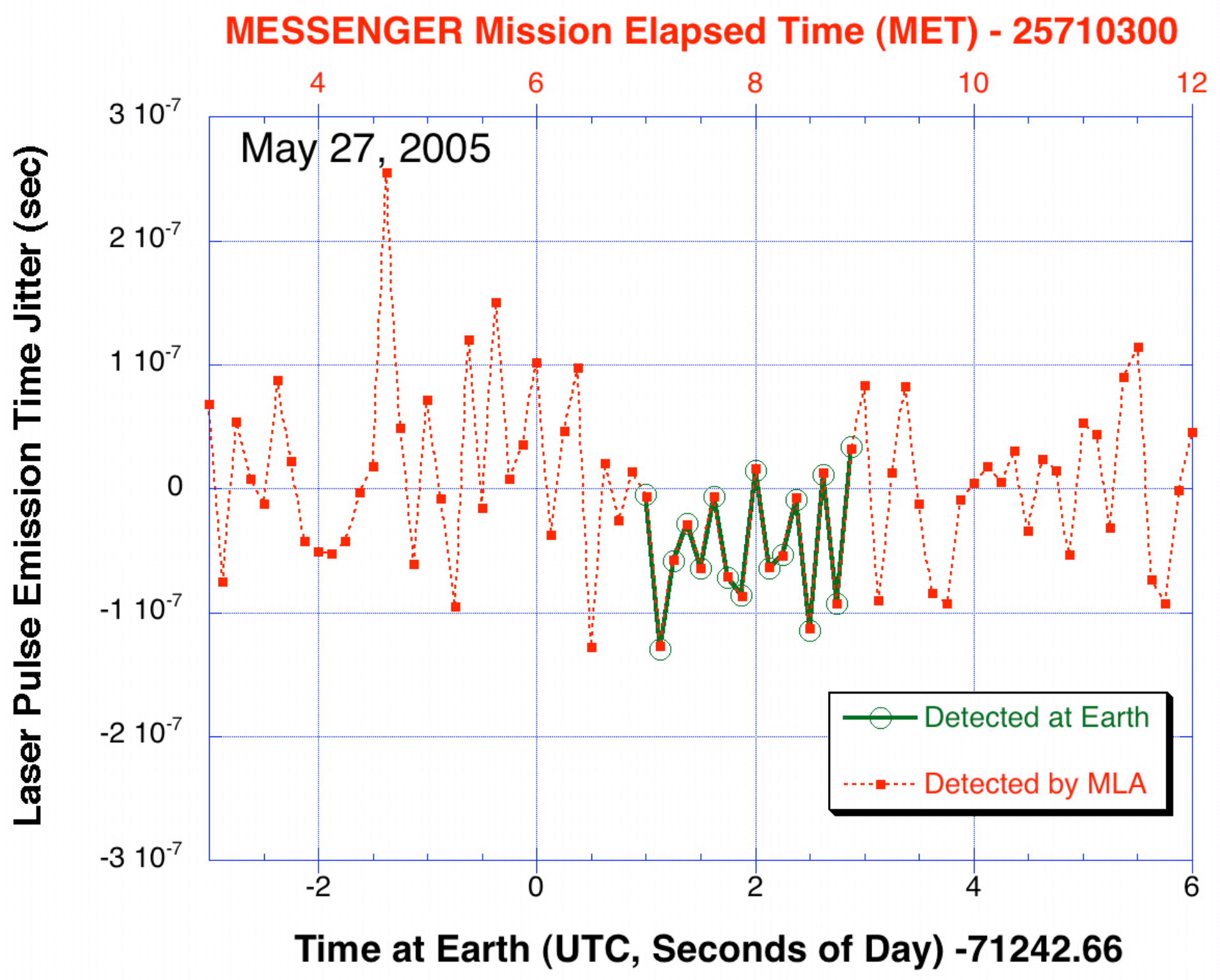


Single (black) and average of 6 waveforms (red) received at GGAO from MLA. Detection threshold is 0.025 V.

4) Detected pulses and timing observables:

The unit of time on the spacecraft is the MET clock, to which all instrument events are synchronized. The laser fires occur irregularly a few hundred microseconds after the T0 8-Hz pulse, and trigger pairs of coarse and fine time counters at high and/or low threshold settings. The MLA fine time count is about 400 ps. The precise rate of MET with respect to Terrestrial Dynamic Time (TDT) and thereby UTC varies by a few parts per billion from day to day. MET is calibrated to UTC periodically with a stipulated accuracy of 1 ms. In practice this may be much better constrained.

The ground pulses also were triggered irregularly, but were timed with a stable clock that was calibrated with respect to GPS receivers. Redundant 100-ps event timers and a 1GHz waveform digitizer allowed precise recording of received pulses. The irregular pulse time arrivals could be easily correlated with the corresponding fire times. The difference between the GGAO detected and the MLA recorded laser jitter was 0.35 ns stdev, corresponding to a ~10 cm one way laser ranging accuracy.



5) Asynchronous asymmetric transponder model

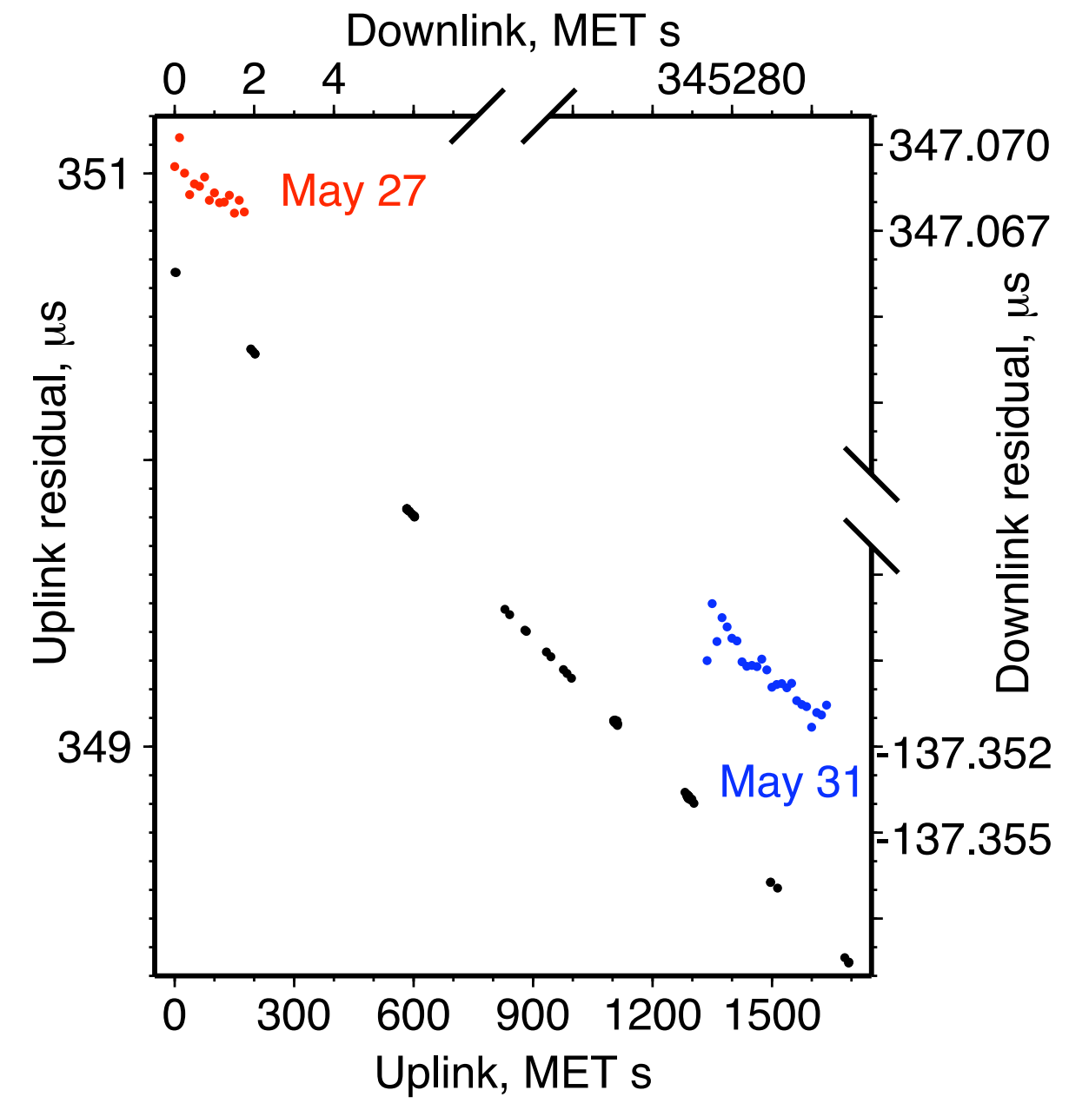
Degnan[2] described two types of laser transponder for deep space ranging and communication. In the synchronous mode, a signal is echoed with a short fixed delay back to the ground station to obtain a two-way range time-of-flight. In the asynchronous mode, two terminals independently fire pulses at each other. In its original concept, the firing rates would match and departure and arrival times of pairs of pulses are matched for analysis at a common receiver. Each pair then allows for the solution for an instantaneous range at a point in time when the pair of photon world lines cross each other. Simultaneously solved for is clock offset, using a correction for the range rate obtained from microwave Doppler tracking.

6) Least-squares fit to data

In the present implementation, far more pulses were fired than received, and the firing rates were not matched. Nor was it necessary to assume an ephemeris for the spacecraft in order to correct for range rate. In fact, we can use the 40 downlink pulses and 90 uplink pulses to solve for clock offset and drift rate, as well as range, range rate, and acceleration, knowing only the approximate position of MESSENGER in the sky so as to correct for the effects of Earth rotation.

7) Comparison with radar tracking ephemeris+clock soln.

Transit time residuals to and from the apparent position of each terminal are shown below using the best reconstructed spacecraft ephemeris[3]. The ground laser pulses (black symbols) were received by MLA ~0.35 ms earlier than predicted. Similarly, the ground receive time of MLA pulses was ~0.34 ms earlier on May 27 (red symbols) but ~0.14 ms later on May 31 (blue symbols). Downlink time scales are foreshortened owing to their much briefer link.

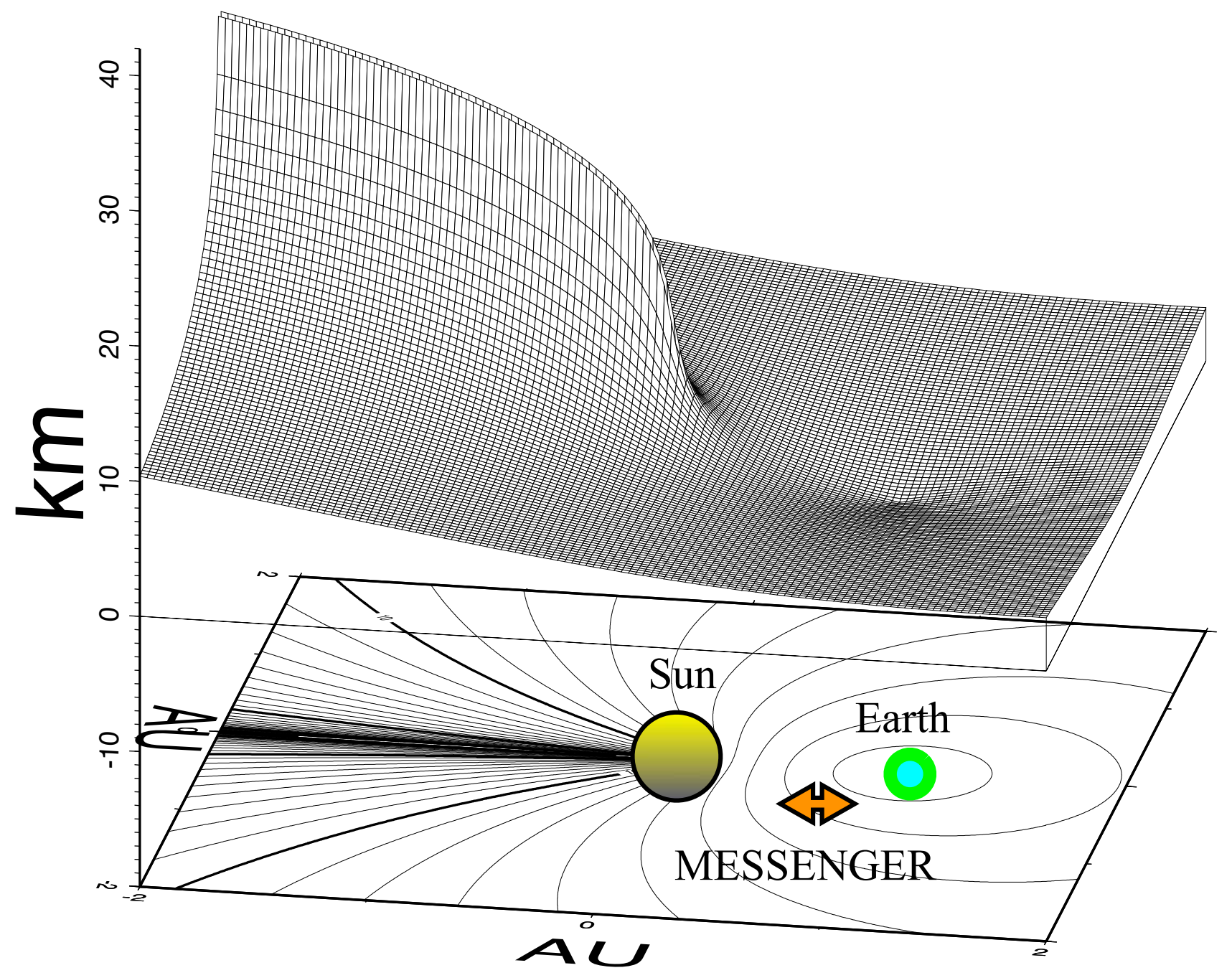


The table compares the least-squares solution with the range at a common time predicted from the JPL ephemeris msgr_20040803_20040903_recon001.bsp using the DE405 planetary ephemeris and the SPICE software toolkit. The clock rate and offset must also take into account the different rate of time at MESSENGER predicted by special relativity.

Parameter	Laser Link Solution	Predicted Spacecraft Ephemeris	Difference(*)
Range, m	23,964,675,433.9±0.2	23,964,674,894.7	539.2
Range rate, m s^{-1}	4154.663±0.144	4154.601	0.062
Acceleration, mm s^{-2}	-0.0102± 0.0004	-0.0087	-0.0015
Time, s	71163.729670967±6.6x10^{-10}	71163.730019659	0.000348692
Clock drift rate, ppb	1.00000001533±4.8x10^{-10}	1.00000001564	-0.5x10^{-10}

8) *General Relativity and light time delay:

Curvature of space time predicted by general relativity affects the path and proper time of light travelling in the vicinity of the Sun's gravitational potential well. Moyer[4] calculates this effect for the case of a single central body, which accounts for 487 m of the 539 m discrepancy. This effect becomes pronounced nearing opposition, amounting to delays equivalent to many km. Laser ranging with 20-cm precision may contribute to tests of Einstein's theory.



9) REFERENCES:

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[2] J.J. Degnan, Asynchronous laser transponders for precise interplanetary ranging and time transfer, *J. Geodynamics* **34**, 551-594, 2002.

[3] Smith, D.E., M.T. Zuber, Z. Sun, G.A. Neumann, J.F. Cavanaugh, J.F. McGarry, and T.W. Zagwodzki, Two-way Laser Link Over Interplanetary Distance, *Science*, in press.

[4] Moyer, T.D., Mathematical formulation of the Double Precision Orbit Determination Program (DPODP), JPL Tech. Report 32-1527, 1971.