P51D-1475

Laser Ranging Experiment on Lunar Reconnaissance Orbiter: Clocks and Ranges

Dandan Mao[1] (dandan.mao@sigmaspace.com), David Rowlands[2], Jan F. McGarry[2], Maria T. Zuber[3], David E. Smith[3], Erwan Mazarico[3], Mark H. Torrence[4], Gregory A. Neumann[2], Xiaoli Sun[2], Thomas W. Zagwodzki[2], John F. Cavanaugh[2], Luis A. Ramos-Izquierdo[2]

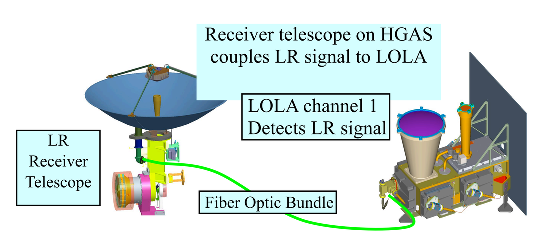
([1]Sigma Space Corporation, Lanham, MD 20706, USA; [2]Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; [3]Department of Earth, Atmospheric and Planetary Sciences, MIT, Cambridge, MA 02129, USA; [4]Stinger Ghaffarian Technologies, Greenbelt, MD 20770 USA)

Abstract

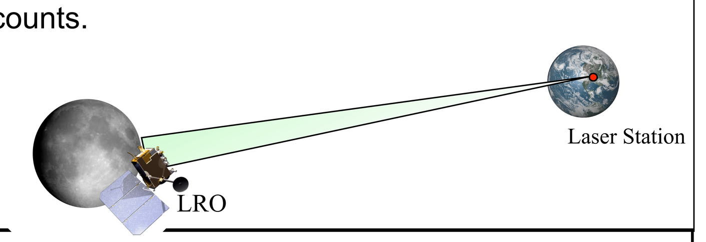
Accurate ranges from Earth to the Lunar Reconnaissance Orbiter (LRO) spacecraft Laser Ranging (LR) system supplement the precision orbit determination (POD) of LRO. LRO is tracked by ten LR stations from the International Laser Ranging Service (ILRS), using H-maser, GPS steered Rb, and Cs standard oscillators as reference clocks. The LR system routinely makes one-way range measurements via laser time-of-flight from Earth to LRO. Uplink photons are received by a telescope mounted on the high-gain antenna on LRO , transferred through a fiber optic cable to the Lunar Orbiter Laser Altimeter (LOLA), and timed-tagged by the spacecraft clock. The range from the LR Earth station to LRO is derived from paired outgoing and received times. Accurate ranges can only be obtained after solving for both the spacecraft and ground station clock errors. The drift rate and aging rate of the LRO clock are calculated from data provided by the primary LR station, NASA's Next Generation Satellite Laser Ranging System (NGSLR) in Greenbelt, Maryland. The results confirm the LRO clock oscillator mid to long term stability measured during ground testing. These rates also agree well with those determined through POD. Simultaneous and near-simultaneous ranging to LRO from multiple LR stations in America, Europe, and Australia has been successfully achieved within a 10 hour window. Data analysis of these ranging experiments allows for precision modeling of the clock behaviors of each LR ground station and characterization of the station ground fire times.

Lunar Reconnaissance Orbiter (LRO) – Laser Ranging (LR) Overview

- Flight Segment:
  - 3.81 cm diameter aperture mounted on High Gain Antenna
  - Fiber optic bundle carries the light to the LOLA detector #1
  - LR FOV is ~ 1.7 deg (earth diameter is ~2 deg as viewed from moon)
  - 532 nm bandpass filter with 0.3 nm FWHM
  - Ultrastable OCXO oscillator: Symmetricom 9500 (2x10-12 over 1 hour)
  - Onboard software controls threshold setting using detector noise counts.

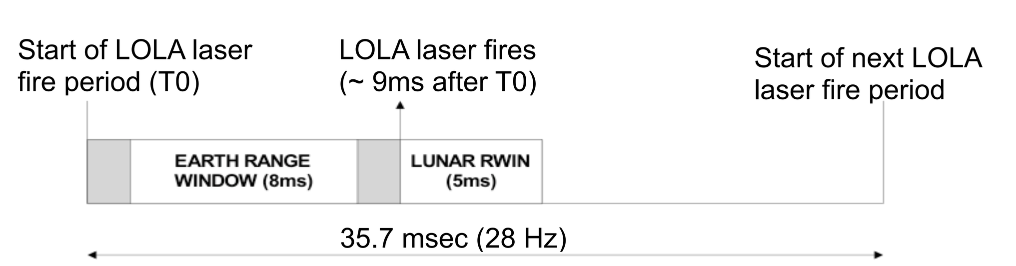


- Ground Segment:
  - Transmit 532 nm laser pulses at =< 28Hz
  - Time stamp departure times at ground station



One LOLA Detector does both Earth and Lunar Measurements

- Two range windows in one detector: 8 msec earth and up to 5 msec lunar.
- Range to LRO changes ~ 5-10 ms over an hour's visibility.
- either
  - synchronize the ground laser fires to LOLA's fire window and LRO's orbit to ensure pulses land in every Earth Window, or
  - fire asynchronously to LOLA (eg 10Hz).

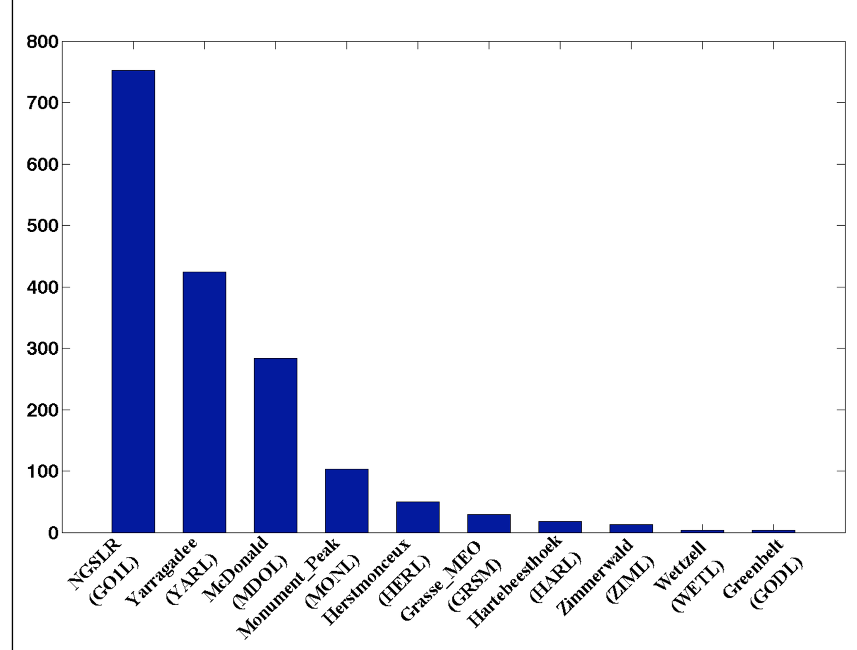


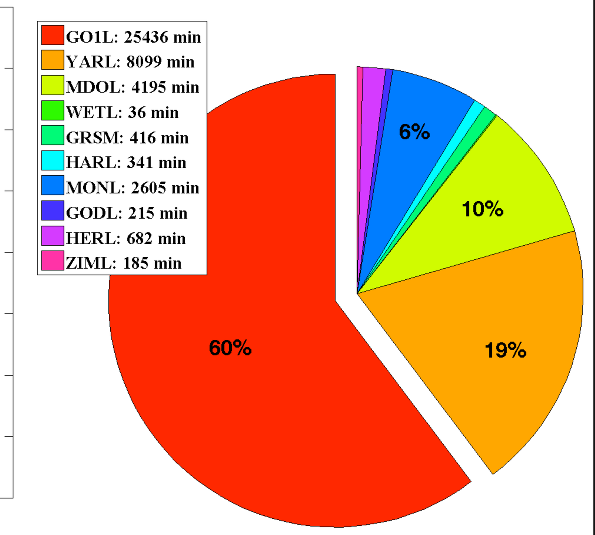
Participating Stations from the International Laser Ranging Service (ILRS)

- Fire times recorded at each station:
  - Accuracy to UTC < 100 ns
  - Relative fire time error RMS < 200 ps (over 10 sec).
- NASA's Next Generation Satellite Laser Ranging System (NGSLR):
  - 50 mJ Northrop Grumman laser (532.2 nm wavelength, 6 ns pulsewidth).
  - Symmetricom Cesium oscillator (CS-4310) / Hydrogen-Maser provides 10 Mhz time base for ET.
  - Arcsecond precision tracking mount, pointing accurate to a few arcseconds.
  - Resolution of recorded time of each shot: <100 psec resolution

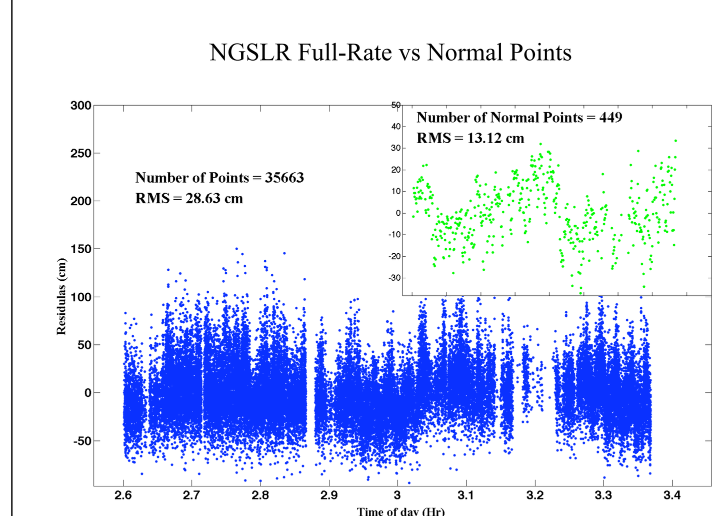
Tracking station	Synchronous	FireRate	Events/second in Earth Window	Energy per pulse at LRO (fJ/cm²)
NGSLR (Greenbelt,MD,USA)	YES	28Hz	28	2 to 5
McDonald (TX,USA)	NO	10Hz	2 to 4	4 to 10
Monument Peak (CA,USA)	NO	10 Hz	2 to 4	1 to 2
Yarragadee (Australia)	NO	10 Hz	2 to 4	1 to 2
Hartebeesthoek (South Africa)	NO	10 Hz	2 to 4	1 to 2
Greenbelt (MD, USA)	NO	10Hz	2 to 4	1 to 2
Herstmonceux (Great Britain)	YES	14Hz	14	1 to 3
Zimmerwald (Switzerland)	YES	14Hz	14	2 to 10
Wettzell (Germany)	NO	7 Hz	7	1 to 2
Grasse (France)	NO	10Hz	2 to 4	1 to 2

LR Data Summary
From July 3, 2009 to December 3, 2010





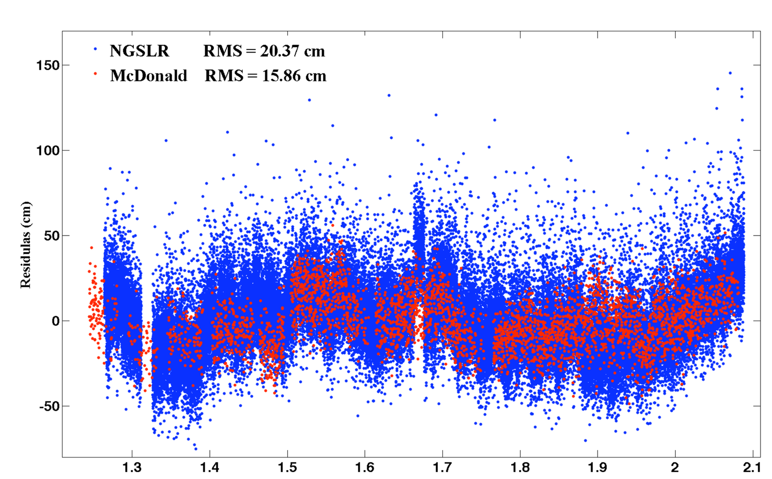
LR Data Structure and Precision

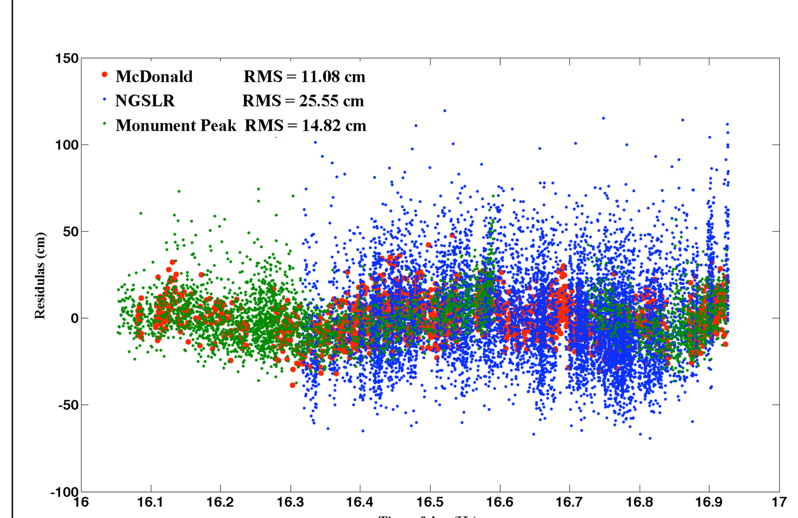


- Use predictions (CPFs) generated by GSFC Flight Dynamics Facility (FDF) with accuracy < 1 km (3D, 3 sigma)
- Event arrival times recorded by LOLA
- Earth tracking stations fire time files are combined with LRO "Earth window" receive times calculating time of flight considering relativistic effects to match the fire and receive times every morning to form 1-way laser range observations
- The resulting "full-rate" observations are aggregated to form normal points every 5 seconds
- One way LR precision: 30 cm

Simultaneous LR Tracking

- 2-way simultaneous tracking obtained from:
  - NGSLR & McDonald: 51 passes
  - NGSLR & Monument Peak: 9 passes
  - NGSLR & Greenbelt: 2 passes
  - McDonald & Monument Peak: 3 passes
  - Grasse & Zimmerwald: 1 pass



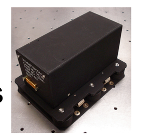


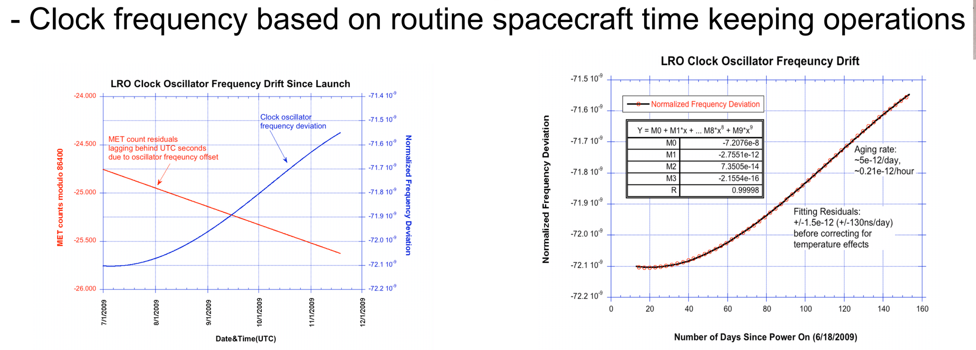
- 3-way simultaneous tracking from:
  - NGSLR & McDonald & Monument Peak
  - 14 passes obtained
- Almost simultaneous tracking have also been regularly obtained from up to 5 LR stations within 10 hours
- Behavior of ground station clocks can be monitored by these simultaneous/ almost-simultaneous data

LOLA/LR Clock Oscillator Characteristics

Mid to Long Term Stability per s/c house keeping data

Symmetricom 9500 series Oven Controlled Crystal Oscillator
Size: 180x130x110 cm; Mass: 2.5 kg; Power: 4.5 W.
- Clock frequency based on routine spacecraft time keeping operations

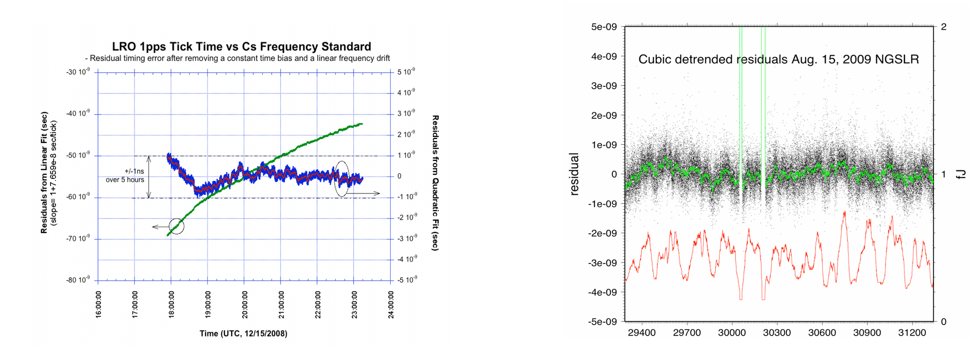




- Oscillator long term frequency stability is about +/-1.5e-12 per day before removing the temperature effect.
- Large thermal mass smoothes out orbital temperature effect
- Daily and long term temperature effects can be removed to <<1e-12 using the model developed during ground testing.

Frequency Stability via LR data

Pre-launch LR Test Data during TVAC — In-orbit LR Measurement Data



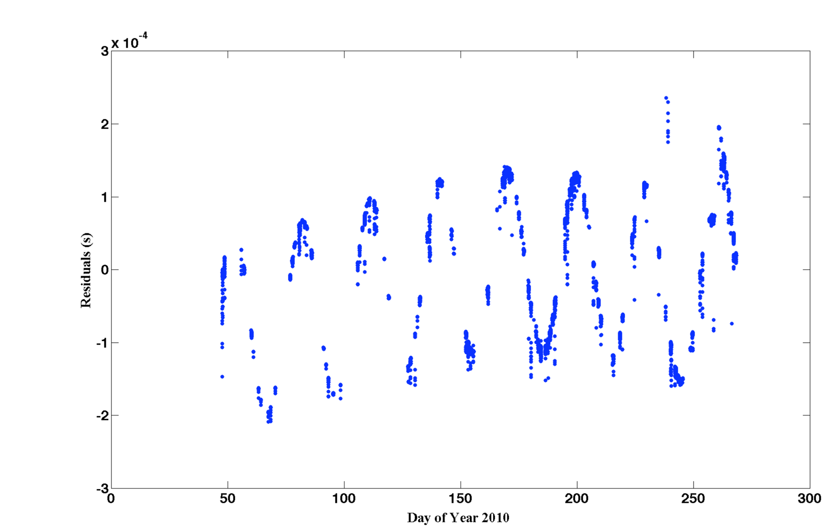
- LRO time base is stable to a few nanoseconds over several hours after removing a linear frequency aging rate based on both ground testing data and in orbit data.
- LR measurements helped to verify the spacecraft time (e.g., LRO MET counter reading 8326775 9/23/09 00:00:00.321424484 (UTC))

LRO Clock Drift and Aging Rates
(Without removing Temperature effect)

	Drift Rate	Aging Rate
Pre-launch Test	-1.00000007659	2.89351852E-17
POD	-1.00000007052	2.24714362E-17
LR (NGSLR)	-1.00000007108	2.25257571E-17

- The drift rate of the LRO project-supplied spacecraft clock is approximately 1.00000007178 seconds per 1 pps clock tick.
- The drift rate and aging rate calculated from NGSLR LR data confirmed the LRO clock measurements during ground testing, and agreed well with results from precise orbit determination (POD)
- The plot shows the relativistic monthly effect as expected
- Thus the clock offset for Laser Ranging and LOLA can be predicted much more easily just using this rate, obviating the need for the SCLK and LRO to LOLA time offsets (STCF).

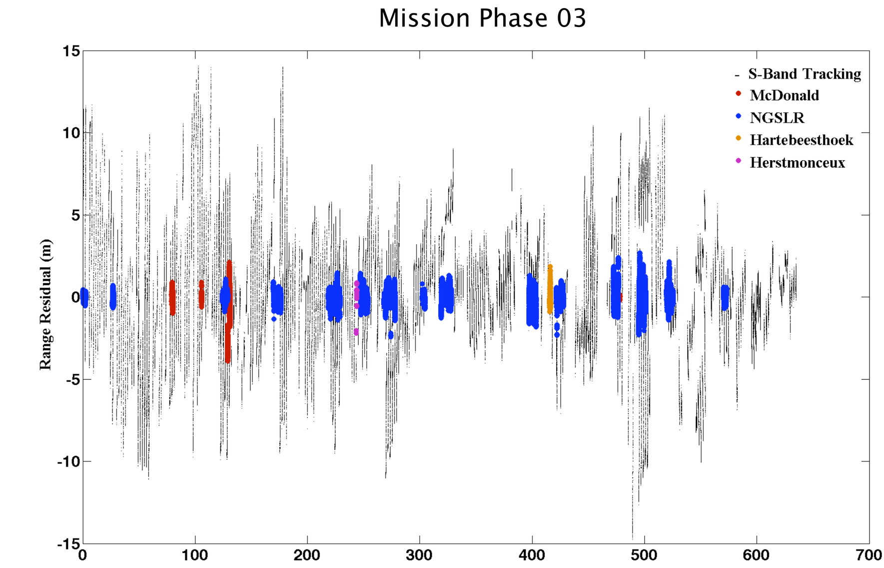
Residual = LRO MET – NGSLR UTC – Light Time – offset_drift_aging



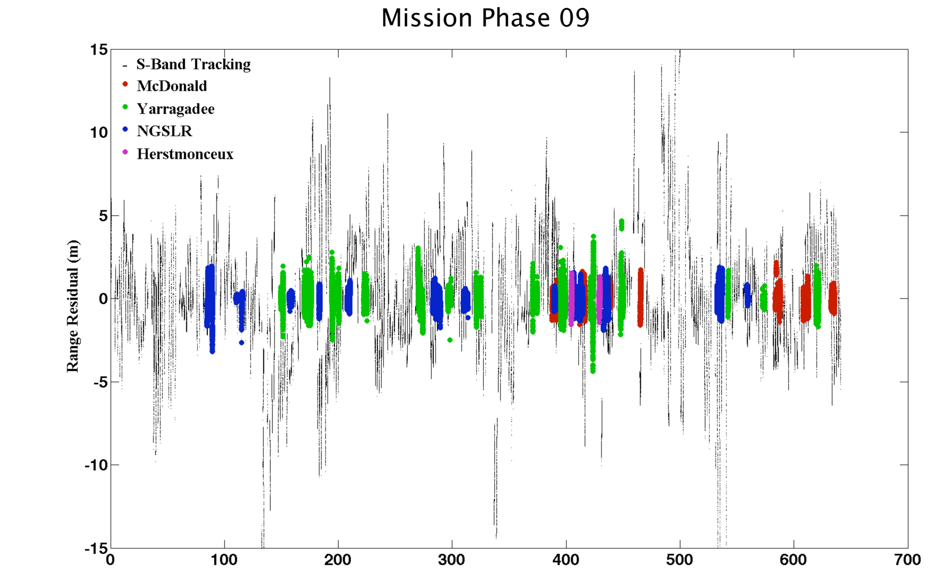
LRO Orbit Determination Results with LR

Range Residuals: LR vs S-Band Range

Mission Phase 03



Mission Phase 09



Orbit Differences: S-Band (Doppler+Range) vs S-Band (Doppler+Range)+LR

	Residual RMS (m) /Number of Observations per LR Station							Orbit Differences			
Phase	NGSLR	YARL	MDOL	HERL	GRSM	HARL	WETL	Radial (m)	Cross (m)	Along (m)	Total (m)
NO_01	0.45/21626	-/0	0.31/399	1.31/1190	-/0	-/0	-/0	14.69	1.65	30.00	56.16
NO_02	0.40/23920	-/0	0.49/2492	1.14/568	-/0	-/0	0.57/360	9.20	2.27	25.12	57.07
NO_03	0.52/34438	-/0	4.26/1792	0.80/20	-/0	0.50/251	-/0	47.36	1.49	52.14	63.90
NO_04	0.39/14692	-/0	0.58/951	0.41/7	-/0	-/0	-/0	10.82	0.90	20.80	60.32
NO_05	0.55/32044	1.24/9716	0.63/2332	1.16/701	-/0	-/0	-/0	20.36	1.50	27.31	62.38
NO_06	0.52/10592	1.35/3803	0.75/4707	0.86/1113	-/0	-/0	-/0	9.22	1.54	14.28	56.64
NO_07	0.45/21725	0.83/7820	0.59/6690	0.74/289	-/0	-/0	-/0	17.77	2.40	32.06	58.92
NO_08	0.47/23615	1.00/9314	0.66/5079	0.91/2152	-/0	-/0	-/0	18.84	1.77	29.18	56.88
NO_09	0.57/21399	0.84/7853	0.49/5104	0.57/660	0.91/196	-/0	-/0	37.83	2.08	47.17	58.47