Supplementary material for "Rapid Earthquake Rupture Duration Estimates from Teleseismic Energy Rates, with Application to Real-Time Warning

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TACER Results and Energy Distribution in the 2011 Tohoku-Oki Earthquake:

Because we evaluate the cumulative energy over the TACER duration, we can also evaluate any variations in rupture energy with distance and azimuth. While *Venkataraman and Kanamori* [2004] showed that for dip-slip earthquakes teleseismic estimates of energy only vary by a factor of 2 depending on orientation relative to directivity, we found that in the case of the 2011 Tohoku-Oki earthquake, energy estimates varied by as much as an order of magnitude, with the maximum determination in the hemisphere to the west (downdip) of the rupture (Figure 3c,d). Many stations in a swath between Australia, clockwise through Scandinavia showed substantially higher rupture energies (western hemisphere average E = 4.0e16 J) than did stations to the east (Eastern hemisphere average E = 6.40e15 J). This discrepancy is intriguing, but a clear identity to the cause is yet unknown, and worth investigating.

Directivity Effects:

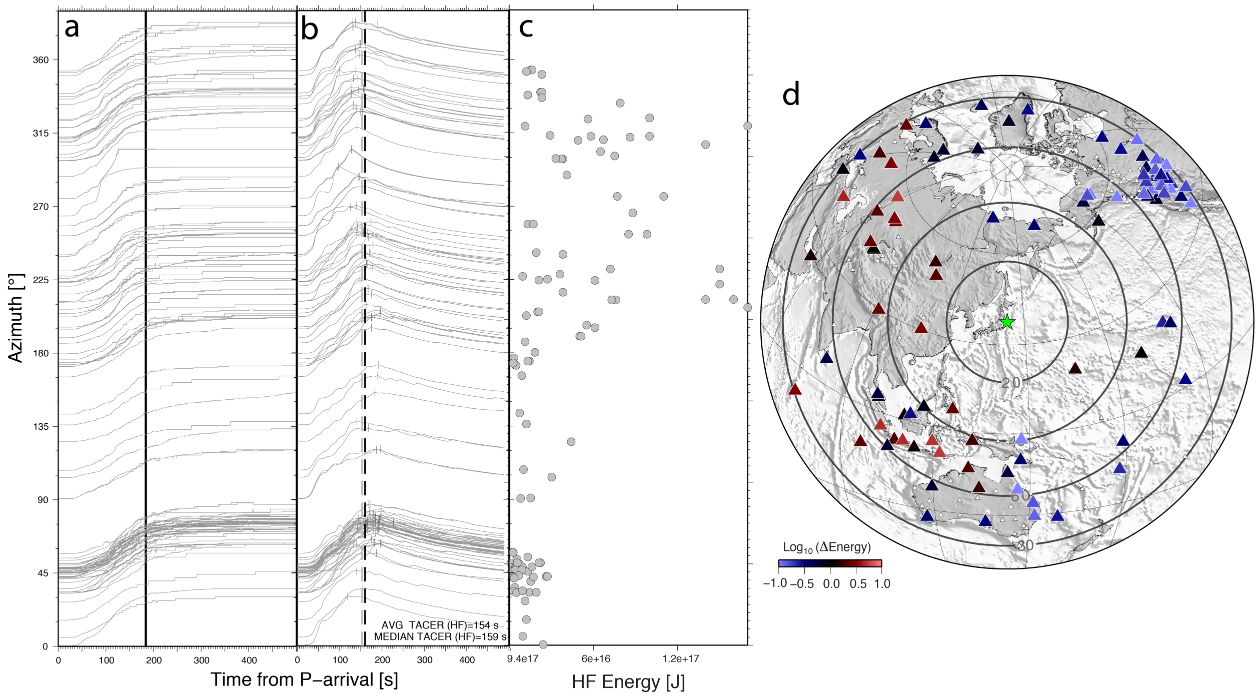
Because we evaluate T_R from stations that are azimuthally distributed, we can explore the applicability of the method to identify rupture directivity. Directivity manifests in shorter apparent durations in the direction of rupture propagation and longer durations in the opposite direction [*Stein and Wysession*, 2003], similar to a Doppler shift but in duration rather than frequency. Such a real-time estimation, when combined with the hypocenter, can be useful for evaluating the extent of the rupture area; useful for evaluating damage and tsunami potential.

An earthquake's rupture is not a point source, but is a continuum of transient sources radiating across a fault over the event's duration [*Douglas et al.*, 1988]. Thus, directivity effects can be seen when a sufficiently long and unilateral rupture occurs causing changes in the apparent rupture duration with azimuth [*Caldeira et al.*, 2010]. The rupture duration will appear shorter when the rupture is moving toward the observing station and longer when it is moving away from the station. This can also be used to differentiate the fault plane from the auxiliary plane in the case of strike-slip faults [e.g. *Warren and Silver*, 2006]. In a simplified way, the observed apparent duration T_{app} and its change with azimuth Φ can be expressed as [*Stein and Wysession*, 2003]:

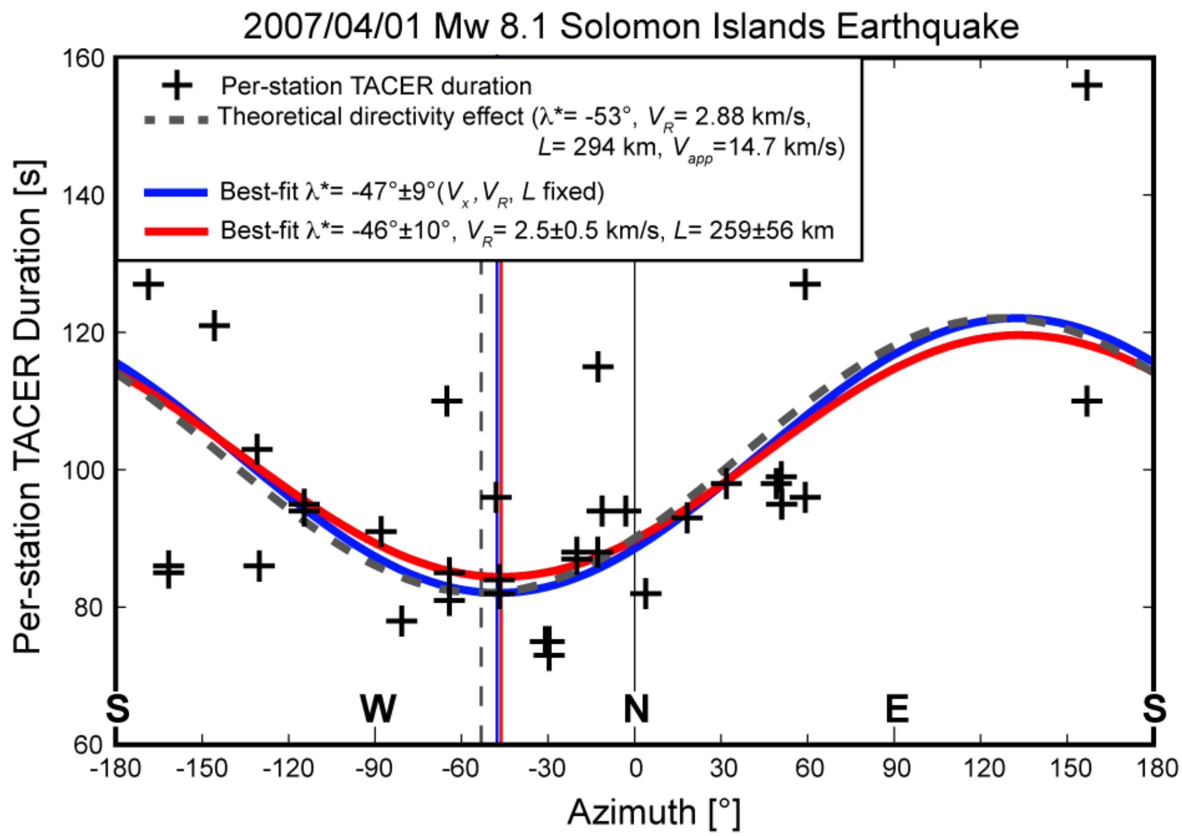
$$T_{app} = \frac{L}{V_r} - \frac{L}{V_{app}} \cos(\phi - \lambda^*) \ , \qquad (1)$$

where the fault length L over the rupture velocity V_r (the true rupture duration T_R), V_{app} is the apparent *P*-wave velocity, and λ^* is the rupture propagation direction.

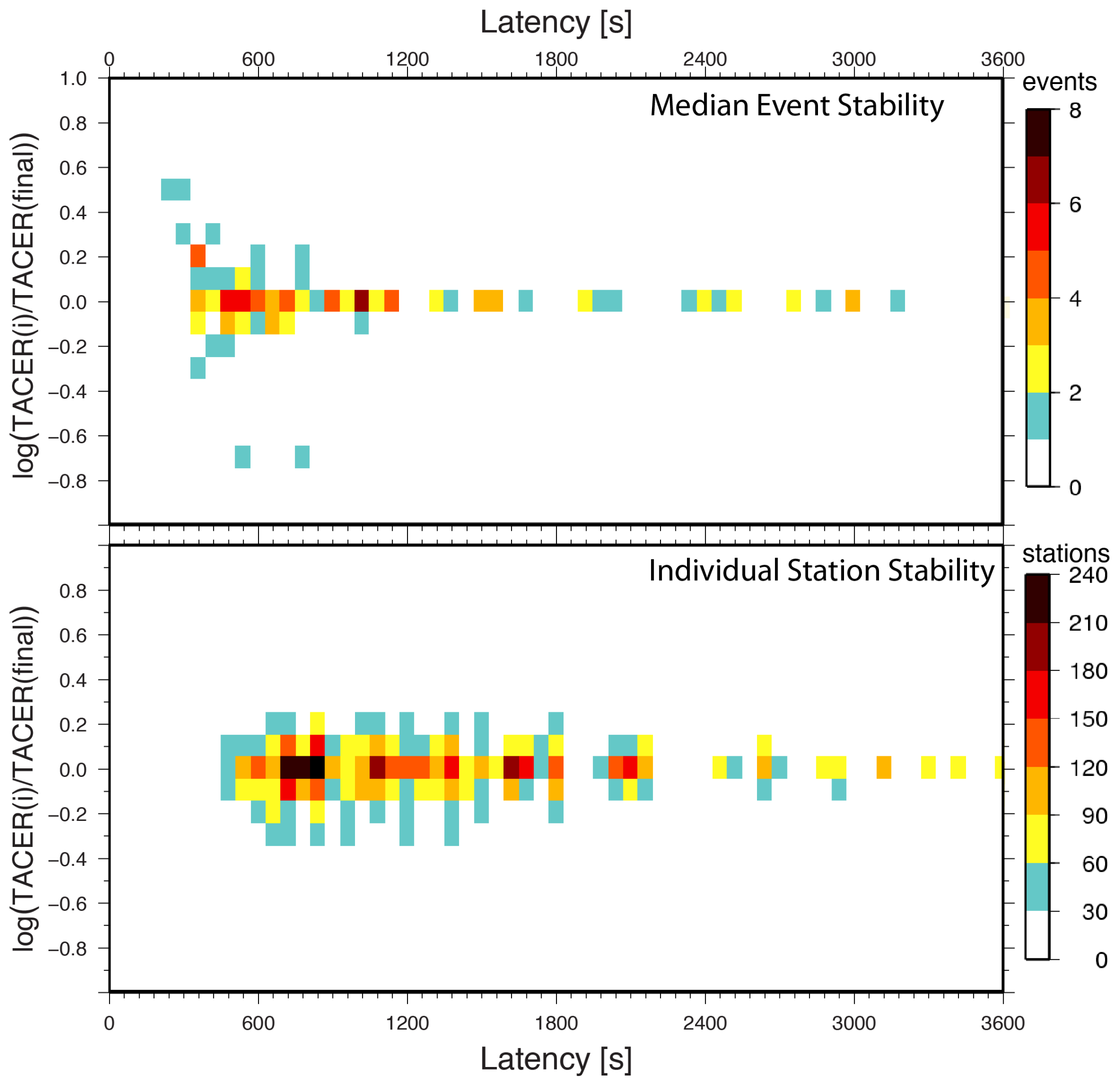
For a long and largely unilaterally rupturing earthquake with good azimuthal station coverage, such as the 2007 M_W 8.1 Solomon Islands event, it is possible to extract important earthquake parameters from the directivity effects on T_{TACER}. We Illustrate this by comparing the theoretical to best-fit estimates of the apparent rupture duration using known and predicted values for each rupture length L, orientation of rupture λ^*, and rupture velocity $V_{R.}$ The theoretical effect is estimated for an apparent velocity at 50° distance (V_{app} = 14.7 km/s), using geometric parameters from *Chen et al.,* [2009] (L=294 km, and λ^{*}=-53°), and rupture velocity determined from the product of L over T_{TACER} (yielding V_R=2.88 km/s). We find that this theoretical result is statistically equivalent to the best-fit directivity result solving simultaneously for orientation, rupture velocity, and rupture length (λ^{*}= -46°±10°, V_R = 2.5 ± 5 km/s, and L = 259 ± 56 km at one standard deviation) (Supplementary Figure 2). While the results are remarkable for this near-ideal case, showing that it is possible to constrain the approximate direction, length of rupture and rupture velocity, such results may only be achieved when earthquakes have long unilateral rupture and good azimuthal coverage. Because there remains a strong trade-off between V_R and L, one or both parameters may need to be fixed for most attempts at constraining directivity.



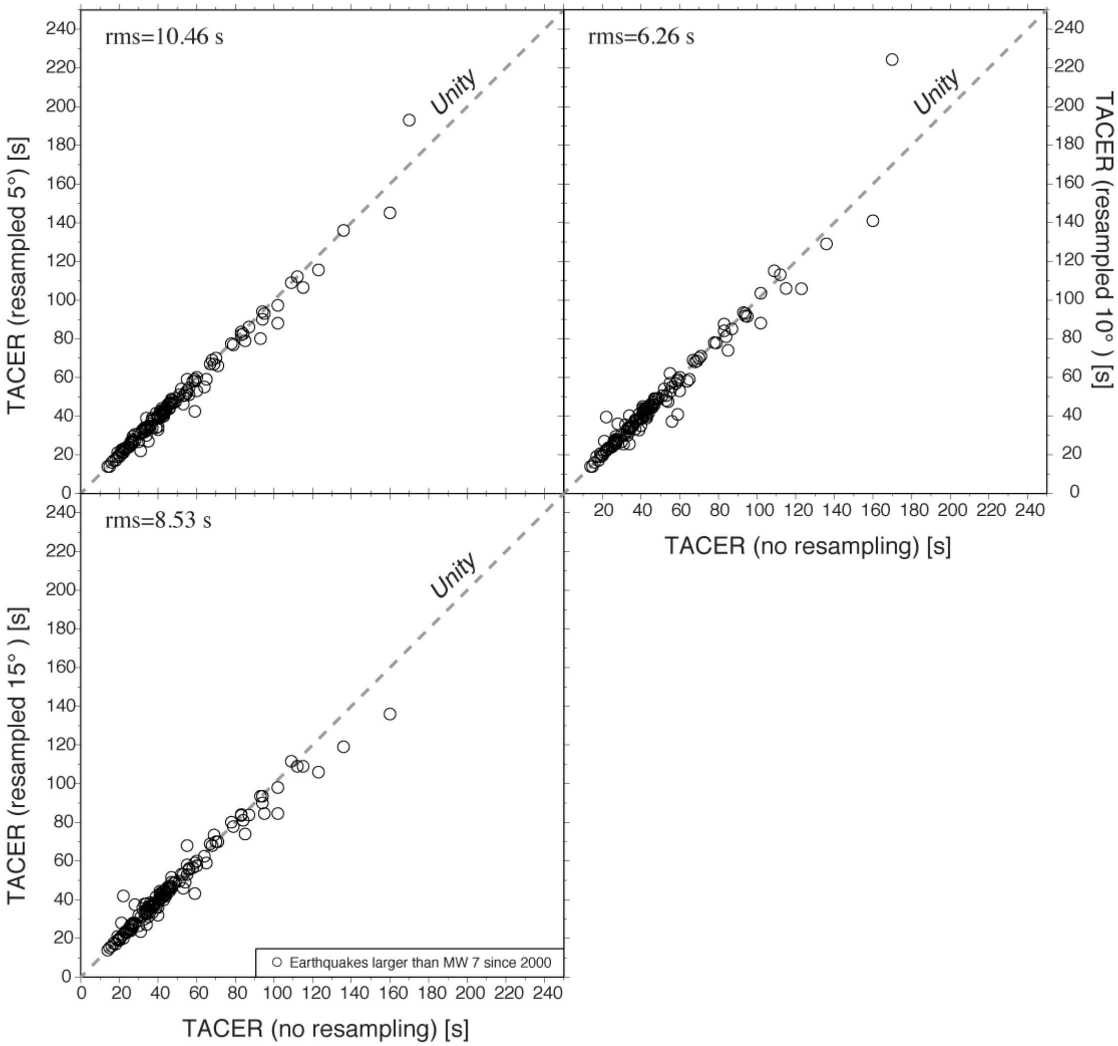
Supplementary Figure 1: The azimuthal and spatial distribution of high-frequency energy is shown for the M_W 9.0 Tohoku-Oki earthquake. For each of the 125 stations, the normalized azimuthal distribution of the **(a)** cumulative energy, and **(b)** TACER are shown. Also shown are **(c)** the azimuthal and **(d)** spatial distribution of the per-station energy calculation (relative to the mean in (d)).



Supplementary Figure 2: Azimuthal distribution of the per-station T_{TACER} for high frequency (0.5-2 s) stations recording the 1 April 2007 Solomon Islands earthquake (dark crosses). This event was chosen because it is known to be a large and unilateral rupture propagating from ESE to WNW. The theoretical directivity effect (gray dashed sinusoid) is comparable to best-fit models solving for just orientation (λ*; blue sinusoid), or for each λ*, rupture velocity V_R, and rupture length L (red sinusoid).



Supplementary Figure 3: Stability and latency of TACER results for events gathered by RTerg beginning in 2009. We plot the ratio of the median (top) and individual (bottom) TACER solution relative to the final median TACER solution as a function of solution latency from event origin.



Supplementary Figure 4: Because station spacing is uneven, and at times locally very dense (e.g. the U.S. Transportable Array), we evaluated the potential for biasing. To do this, we choose a median solution every (a) 5°, (b) 10° and (c) 15° and use this as a new individual TACER solution to find a new event median. These results are all compared with the original results without resampling (*x*-axes). As sampling radius increases, solutions increasingly differ, however rms offsets remain small (~8, 6, and 10 s for 5°, 10°, and 15° cases respectively), indicating that azimuthal biasing is not a widespread issue.

Supplementary table 1: Events with their TACER and T-crossover. Estimated durations.

For TACER durations we include the upper and lower 75%

Date	HH:MM	M_W	M_r	$\phi/\delta/\lambda$	T_{TACER} (s)	T_{TACER} Lower 75% (s)	T_{TACER} Upper 75% (s)	T_{XO} (s)
2000/01/08	16:47	7.2	7.24	79/8/347	27	23	30	24
2000/03/28	11:00	7.6	7.97	255/6/233	26	22	30	40
2000/05/04	04:21	7.5	7.87	225/64/172	49	33	94	64
2000/05/12	18:43	7.1	7.00	214/12/298	20	16	26	20
2000/06/04	16:28	7.8	8.24	92/55/152	59	38	115	79
2000/06/18	14:44	7.9	7.82	161/63/355	36	24	49	48
2000/08/06	07:27	7.3	7.40	108/27/218	23	17	28	24
2000/11/16	04:54	8.0	7.99	328/43/3	136	78	159	84
2000/11/16	07:42	7.8	7.42	253/15/93	79	36	112	76
2000/11/17	21:01	7.8	6.90	230/24/64	69	38	93	95
2001/01/01	06:57	7.4	7.27	171/45/60	60	41	80	69
2001/01/13	17:33	7.7	7.87	121/35/265	40	25	51	48
2001/01/26	03:16	7.6	7.71	298/39/136	31	26	36	26
2001/02/13	19:28	7.3	7.07	315/16/103	47	39	63	63
2001/06/03	02:41	7.1	7.33	227/41/138	23	20	28	21
2001/08/21	06:52	7.1	7.46	55/42/116	70	51	111	72
2001/10/19	03:28	7.5	7.63	358/77/176	55	44	77	67
2001/11/14	09:26	7.8	7.58	94/61/348	123	62	181	150
2002/01/02	17:22	7.2	7.42	299/18/22	43	28	59	50
2002/03/05	21:16	7.5	7.27	314/25/70	54	39	71	83
2002/03/31	06:52	7.1	7.03	292/32/121	39	20	52	49
2002/06/28	17:19	7.3	7.72	27/13/105	24	19	31	25
2002/08/19	11:01	7.6	8.23	149/22/219	22	19	26	25
2002/09/08	18:44	7.6	7.54	106/34/43	45	37	57	82
2002/10/10	10:50	7.5	7.82	60/83/4	102	33	148	100
2002/11/02	01:26	7.2	7.27	297/16/73	49	39	60	70
2002/11/03	22:12	7.8	7.75	296/71/171	26	22	73	80
2002/11/17	04:53	7.3	7.59	316/9/30	14	13	24	20
2003/01/22	02:06	7.5	7.27	308/12/110	39	20	63	50
2003/07/15	20:27	7.5	7.56	307/69/1	87	73	101	85
2003/08/04	04:37	7.5	7.49	101/36/337	43	34	51	52
2003/08/21	12:12	7.2	7.27	35/23/95	30	19	42	40
2003/09/25	19:50	8.3	8.04	250/11/132	71	53	96	95
2003/09/25	21:08	7.3	7.43	208/18/86	64	44	76	69
2003/09/27	11:33	7.2	7.39	228/70/20	38	28	144	50
2003/12/27	16:00	7.2	7.10	324/29/95	46	37	54	55
2004/01/03	16:23	7.1	7.09	314/39/283	34	23	44	40
2004/02/07	02:42	7.3	7.53	261/68/353	41	26	50	60
2004/07/25	14:35	7.3	7.85	108/45/231	20	14	25	25
2004/09/05	10:07	7.2	7.41	277/38/100	34	22	47	48

2004/09/05	14:57	7.4	7.51	79/46/72	51	46	64	55
2004/11/11	21:26	7.5	7.89	67/27/72	46	39	55	55
2004/11/15	09:06	7.2	7.44	21/11/114	53	12	87	85
2004/11/22	20:26	7.1	7.09	43/36/103	40	22	66	45
2004/11/26	02:25	7.1	7.14	5/34/0	40	30	89	67
2004/12/23	14:59	8.1	8.23	69/74/167	53	39	71	75
2004/12/26	00:58	9.0	8.71	329/8/110	170	131	271	540
2005/02/05	12:23	7.1	7.14	158/14/246	16	13	24	45
2005/03/02	10:42	7.1	7.60	308/35/176	15	11	33	73
2005/03/28	16:09	8.6	8.43	333/8/118	94	78	104	93
2005/06/13	22:44	7.8	7.83	182/23/279	19	17	26	74
2005/06/15	02:50	7.2	7.14	317/83/175	33	25	47	42
2005/07/24	15:42	7.2	7.49	29/68/358	36	29	45	46
2005/08/16	02:46	7.2	7.09	194/16/81	45	25	72	56
2005/09/09	07:26	7.6	7.31	140/30/91	84	64	155	90
2005/09/26	01:55	7.5	7.33	347/39/268	17	14	55	82
2005/10/08	03:50	7.6	7.41	334/40/123	40	33	56	65
2006/01/02	06:10	7.4	7.44	358/77/192	27	23	35	36
2006/01/02	22:13	7.2	7.39	281/22/320	18	12	23	25
2006/01/27	16:58	7.6	8.01	43/42/316	28	25	35	30
2006/04/20	23:25	7.6	7.26	207/40/76	41	28	53	55
2006/05/03	15:26	8.0	8.26	226/22/123	59	36	82	80
2006/05/16	10:39	7.4	7.69	129/19/58	26	21	32	35
2006/07/17	08:19	7.7	7.05	290/10/102	109	72	155	160
2006/11/15	11:14	8.3	7.93	215/15/92	95	73	111	115
2007/01/13	04:23	8.1	8.18	266/39/306	68	54	87	100
2007/01/21	11:27	7.5	7.53	34/35/108	37	30	44	40
2007/03/25	00:40	7.1	7.15	333/36/89	37	27	43	31
2007/04/01	20:39	8.1	7.91	333/37/121	94	81	115	101
2007/08/01	17:08	7.2	7.46	356/29/79	27	23	84	45
2007/08/08	17:04	7.5	7.64	330/30/155	33	24	40	30
2007/08/15	23:40	8.0	7.89	321/28/63	115	62	138	155
2007/09/02	01:05	7.2	7.19	338/23/101	65	42	76	82
2007/09/12	11:10	8.5	8.26	328/9/114	102	89	125	108
2007/09/12	23:48	7.9	7.64	317/19/102	93	46	107	108
2007/09/28	13:38	7.5	7.56	73/49/50	19	15	29	24
2007/09/30	05:23	7.4	7.41	29/36/123	44	39	55	57
2007/10/31	03:30	7.2	7.37	196/60/152	25	12	85	25
2007/11/14	15:40	7.7	7.77	358/20/98	59	50	73	71
2007/11/29	19:00	7.4	7.83	109/58/328	25	22	29	24
2007/12/09	07:28	7.8	7.98	34/25/38	34	25	46	35
2007/12/19	09:30	7.2	7.09	274/21/118	35	27	49	41
2008/02/20	08:08	7.3	7.17	299/11/80	58	40	72	64
2008/02/25	08:36	7.2	7.12	317/6/102	47	22	58	52
2008/03/20	22:33	7.1	6.89	358/41/250	36	33	46	38
2008/04/09	12:46	7.3	7.08	340/30/101	43	18	52	49
2008/04/12	00:30	7.1	7.14	3/43/102	25	19	42	30
2008/05/12	06:28	7.9	7.95	231/35/138	83	50	123	100
2008/11/16	17:02	7.3	7.21	92/20/84	46	33	74	60

2008/11/24	09:02	7.3	7.55	276/19/331	27	25	30	30
2009/03/19	18:17	7.8	7.62	205/44/98	28	23	57	65
2009/05/28	08:24	7.5	7.34	63/60/353	41	26	73	48
2009/07/15	09:22	7.6	7.77	25/26/138	55	44	122	58
2009/08/09	10:55	7.0	7.06	86/17/168	18	12	22	19
2009/08/10	19:55	7.4	7.46	39/36/268	56	44	69	57
2009/09/29	17:48	8.1	8.08	119/38/229	83	61	114	93
2009/09/30	10:16	7.7	7.55	74/52/139	34	20	65	70
2009/10/07	22:03	7.5	7.61	344/41/87	43	31	75	63
2009/10/07	22:18	8.1	7.81	337/36/82	78	52	98	103
2009/10/07	23:13	7.9	7.41	341/43/83	37	28	74	38
2009/11/09	10:44	7.2	7.26	172/42/33	38	22	42	29
2009/11/09	10:44	7.5	7.26	172/42/33	73	67	88	78
2010/01/03	22:36	6.9	7.10	321/21/102	44	32	84	78
2010/01/12	21:53	7.3	7.03	152/69/159	33	25	50	36
2010/02/27	06:34	8.6	8.78	19/18/116	119	97	146	142
2010/02/27	08:01	8.0	7.35	3/46/258	32	21	52	35
2010/04/04	22:40	6.7	7.17	221/83/254	63	53	77	108
2010/04/06	22:15	7.5	7.76	308/9/87	70	59	85	68
2010/05/09	05:59	7.1	7.23	308/15/86	47	39	63	58
2010/05/27	17:14	7.1	7.14	162/45/85	36	20	74	83
2010/06/12	19:26	7.5	7.44	116/61/152	42	29	48	60
2010/07/18	13:35	7.2	7.31	259/29/87	52	27	112	80
2010/07/23	22:08	7.1	7.29	259/18/324	27	17	40	34
2010/07/23	22:51	7.7	7.63	235/18/324	26	21	34	33
2010/07/23	23:15	7.6	7.43	257/24/309	22	16	45	33
2010/08/10	05:23	7.4	7.24	355/32/126	30	21	48	56
2010/08/12	11:54	7.0	7.06	151/20/289	16	12	35	35
2010/10/25	14:42	7.1	7.81	319/7/98	85	44	109	127
2010/12/21	17:19	7.7	7.37	115/42/233	42	23	62	56
2010/12/25	13:16	7.5	7.25	150/45/249	41	28	51	59
2011/01/01	09:56	7.3	7.03	1/20/299	13	12	25	226
2011/01/02	20:20	6.9	7.10	2/15/94	32	19	44	37
2011/01/18	20:23	7.1	7.22	78/31/300	44	19	73	54
2011/03/09	02:45	7.2	7.36	189/10/77	46	36	67	67
2011/03/11	05:46	8.5	9.08	203/10/88	158	124	186	179
2011/04/07	14:32	7.4	7.11	19/37/82	34	17	50	60
2011/06/24	03:09	7.4	7.25	15/10/200	37	29	49	53
2011/07/06	19:03	7.6	7.58	163/36/246	44	32	61	72
2011/08/20	18:19	7.0	7.04	343/33/94	44	30	67	49
2011/08/24	17:46	7.2	7.02	197/40/303	18	11	63	19
2011/09/03	22:55	7.0	7.02	19/29/160	22	16	47	98
2011/09/15	19:31	7.7	7.31	312/38/353	21	18	25	29
2011/10/21	17:57	7.5	7.38	202/37/83	48	38	69	71
2011/10/23	10:41	7.0	7.13	246/38/60	26	17	45	41
2012/01/10	18:37	6.3	7.17	105/76/192	60	35	92	89
2012/02/02	13:34	7.2	7.03	53/52/319	44	33	63	68
2012/03/20	18:02	7.9	7.38	295/13/91	41	27	82	38
2012/03/25	22:37	7.1	7.18	21/11/114	48	36	76	61

2012/04/11	08:38	8.1	8.56	20/64/1	112	75	185	146
2012/04/12	07:15	6.6	7.02	41/89/0	51	38	81	76
2012/08/14	02:59	7.9	7.72	25/33/58	27	24	34	70
2012/08/27	04:37	6.5	7.31	287/15/81	55	43	81	72
2012/08/31	12:47	7.7	7.61	345/45/63	34	17	61	51
2012/09/05	14:42	7.3	7.59	317/19/118	42	37	58	60
2012/09/30	16:31	7.4	7.23	228/41/243	27	24	31	32
2012/10/28	03:04	7.3	7.74	320/29/111	67	50	146	69
2012/11/07	16:35	7.1	7.34	296/26/87	35	21	84	37
2012/12/07	08:18	7.6	7.19	18/40/270	52	36	74	75
2012/12/10	16:53	7.4	7.09	310/47/167	56	13	85	138

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