A Sourcebook on the Use of the MU Radar for Satellite Tracking

Version of 2006-09-10

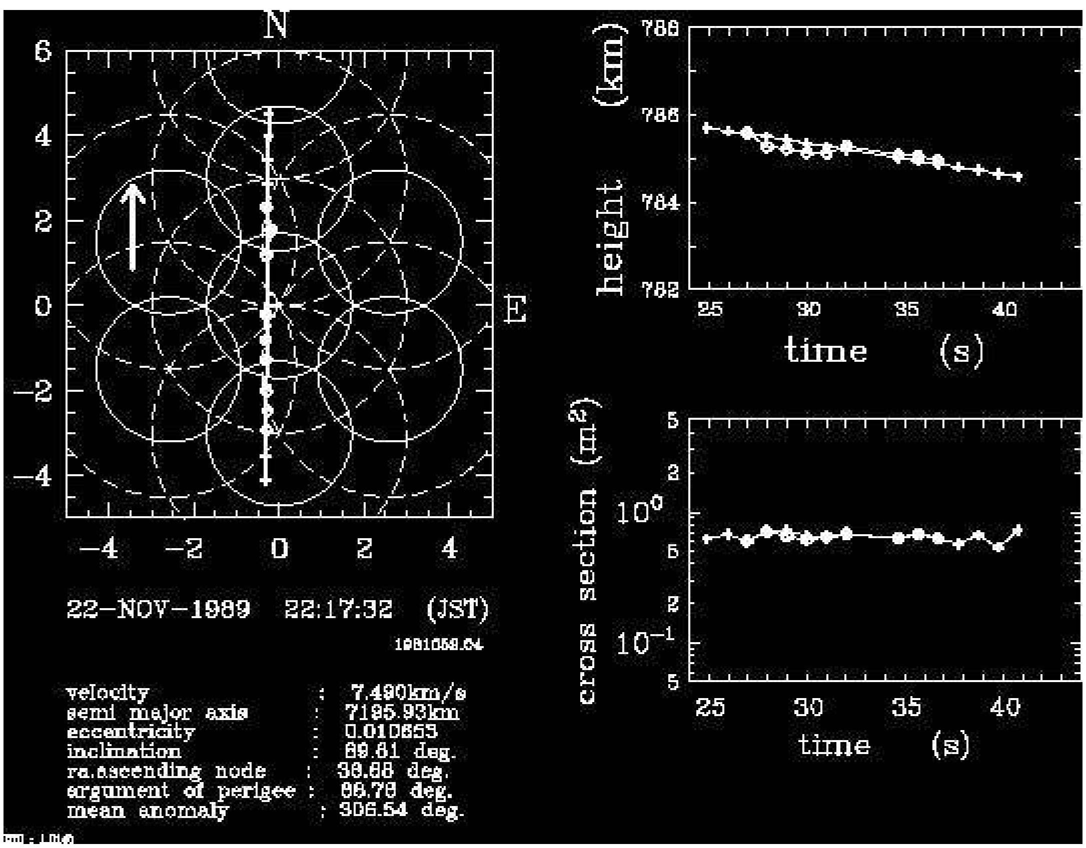
Additional material for this sourcebook would be appreciated
Please send it to thomsona@flash.net

http://www-lab26.kuee.kyoto-u.ac.jp/study/mu/mu_e.html

The MU (Middle and Upper atmosphere) radar was constructed by Radio Atmospheric Science Center of Kyoto University at Shigaraki, Shiga prefecture, Japan (34.85deg N, 136.11deg E) in 1984 mainly for the purpose of investigating atmospheric and plasma dynamics in the wide region from the troposphere to the ionosphere.

The radar is a powerful monostatic pulse Doppler radar operating at 46.5MHz with an active phased array antenna, which consists of 475 crossed Yagi antennas and identical number of solid-state transmit/receive modules. This design realized a very fast beam steerability. The antenna beam direction can be switched to any direction within the steering range of 30deg from zenith from pulse to pulse. The antenna aperture is 8,330m^2 (103m in diameter), and the peak and average output power is 1MW and 50kW, respectively. The antenna beam has a conical shape with the round-trip (two-way) half-power beamwidth of 2.6deg.

Mu Radar Yagi Antenna Elements



Observation of space debris [LCS-4] with the MU Radar

List of debris observed with the MU radar

1-AUG-1989	1:21: 5	408.88	0.778	2.664	7163.83	0.0547	81.7	324.9	29.0	5.9
1-AUG-1989	1:26: 4	765.20	14.868	1.444	7026.39	0.0154	80.3	325.4	231.1	163.9
1-AUG-1989	2:46:14	734.37	45.571	0.778	6614.55	0.0738	34.8	255.1	282.1	173.1
1-AUG-1989	5:35: 5	440.05	4.805	1.266	7182.88	0.0527	70.7	228.7	139.4	3.1
1-AUG-1989	6:47:54	496.92	0.502	2.978	7873.42	0.1293	61.5	255.1	146.8	353.5
1-AUG-1989	6:57:51	788.13	3.395	2.890	6652.92	0.0752	76.2	245.1	325.2	178.8
1-AUG-1989	7:28:59	601.51	28.017	1.052	7195.95	0.0320	83.4	58.4	30.7	4.2
1-AUG-1989	7:33:16	790.87	8.511	0.660	6396.59	0.1187	35.2	330.1	273.6	179.5
1-AUG-1989	8: 1:28	806.95	22.827	1.669	7606.65	0.0572	77.2	259.7	145.5	358.8
1-AUG-1989	8:16:58	773.87	2.257	1.165	7303.94	0.0227	100.2	247.5	150.2	354.5
1-AUG-1989	8:18:48	631.11	4.883	3.866	6187.06	0.1311	76.9	264.3	328.0	175.7
1-AUG-1989	9:43:51	734.43	0.503	3.291	7896.70	0.1047	36.3	23.3	93.3	344.8
1-AUG-1989	10:27:39	517.71	27.207	0.906	6420.40	0.0720	76.4	97.8	216.7	179.2
1-AUG-1989	10:52: 8	760.80	3.214	1.017	5969.53	0.1937	35.1	30.8	264.1	180.2
1-AUG-1989	11:48: 6	800.79	4.565	0.985	7017.05	0.0213	77.8	316.4	319.8	184.5
30-OCT-1989	12:52:22	639.94	5.153	2.268	7711.62	0.0916	84.6	229.1	35.9	359.3
30-OCT-1989	13:30:26	654.09	4.870	0.458	7137.69	0.0170	85.3	65.4	156.6	348.5
30-OCT-1989	15:35:23	615.33	3.803	0.444	7419.19	0.0592	83.8	269.3	35.3	359.8
30-OCT-1989	15:36:46	344.69	18.425	0.796	7162.88	0.0637	85.1	270.4	28.1	6.4
30-OCT-1989	16: 6:32	657.65	5.061	0.645	7558.50	0.0709	100.7	288.9	37.1	358.6
30-OCT-1989	16:13:15	796.98	1.169	2.643	6094.02	0.1754	74.9	272.6	218.1	177.7
30-OCT-1989	16:43:15	796.75	6.683	0.621	6539.17	0.0952	35.2	201.2	271.0	178.4
30-OCT-1989	17:31: 4	663.05	3.133	0.548	6949.38	0.0117	84.1	298.2	228.7	166.3
30-OCT-1989	17:49: 0	593.72	0.517	3.730	6726.71	0.0349	85.2	303.8	206.4	188.8
30-OCT-1989	18:49:41	595.78	0.706	1.562	7102.63	0.0203	84.0	317.9	24.0	10.8
30-OCT-1989	19:33:42	534.41	11.739	1.840	8354.49	0.1742	84.5	329.6	34.5	0.4
30-OCT-1989	20:28:54	649.91	22.374	0.986	7814.57	0.1023	85.6	170.0	144.3	0.7
30-OCT-1989	20:36:14	671.34	7.025	1.269	7524.59	0.0649	66.7	331.5	36.4	1.9
30-OCT-1989	20:58: 5	743.79	0.339	1.394	7655.00	0.0854	97.6	360.0	359.1	33.2
30-OCT-1989	21:22: 7	428.53	2.345	2.244	5984.69	0.1352	69.6	345.6	218.8	178.6
30-OCT-1989	21:22:46	663.88	6.380	0.620	7354.41	0.0444	84.5	356.7	29.7	5.2
30-OCT-1989	23:33:27	794.82	3.872	0.651	7305.62	0.0200	75.7	223.6	138.9	4.8
30-OCT-1989	0:25:57	475.87	15.704	1.656	6728.07	0.0476	76.2	36.7	149.2	249.4
30-OCT-1989	4:36:29	781.26	9.067	0.823	6571.65	0.0875	35.3	28.8	261.2	181.1
30-OCT-1989	6:25:40	802.31	2.767	6.549	7604.60	0.0575	80.1	323.5	145.8	359.0
30-OCT-1989	6:34:56	573.02	7.653	0.489	7462.47	0.0706	84.4	323.1	150.7	354.5
30-OCT-1989	7:29:50	799.45	14.896	1.463	8477.46	0.1550	79.8	339.6	147.1	357.9
30-OCT-1989	8:13:21	765.43	11.287	0.672	7295.92	0.0228	83.0	158.7	40.2	355.1
30-OCT-1989	8:26:34	788.73	13.118	1.274	6268.80	0.1412	35.1	82.4	265.2	180.4
30-OCT-1989	8:37:55	646.88	23.139	0.748	6686.13	0.0487	85.3	353.0	323.3	181.9
30-OCT-1989	9:19:10	645.86	4.158	1.202	6410.12	0.0938	85.8	2.8	323.6	181.6
30-OCT-1989	10: 5:30	352.28	0.068	4.315	5802.57	0.1578	76.4	182.0	213.6	182.7
30-OCT-1989	12:11: 0	788.34	12.525	0.753	7952.17	0.1005	77.9	214.3	34.8	1.0
30-OCT-1989	12:36: 6	522.17	1.136	0.886	11725.72	0.4141	99.8	236.3	43.0	355.6
31-OCT-1990	1:34: 7	472.31	0.314	0.995	7380.90	0.0740	89.3	244.1	150.8	354.8
31-OCT-1990	1:34:35	725.77	10.603	1.373	5965.93	0.1886	35.0	332.0	270.8	180.8
31-OCT-1990	3:55:52	590.08	12.436	2.540	5934.80	0.1720	63.0	300.3	321.4	178.1
31-OCT-1990	4:22:17	813.71	0.321	2.030	7048.96	0.0208	98.8	111.7	242.6	152.2
31-OCT-1990	4:38:22	731.17	3.417	0.861	6377.99	0.1181	36.2	39.5	238.4	197.4
31-OCT-1990	4:42:26	787.60	4.951	0.975	6363.63	0.1240	35.1	17.1	273.7	179.3
31-OCT-1990	4:53:34	483.22	4.949	1.946	6960.02	0.0173	67.4	310.3	164.3	337.9
31-OCT-1990	5:14:24	799.74	2.630	3.767	8442.82	0.1515	99.8	292.2	146.8	358.0
31-OCT-1990	5:34: 9	653.12	3.932	0.865	6965.40	0.0244	69.2	319.0	251.7	251.9
31-OCT-1990	5:36:33	703.69	11.313	1.282	7932.28	0.1090	77.7	313.3	146.6	357.8
31-OCT-1990	6:15:57	751.43	5.146	1.058	6504.33	0.0942	35.3	32.9	277.1	182.4

31-OCT-1990	6:46:16	611.47	14.453	1.044	6521.65	0.0698	84.3	325.5	323.6	181.5
31-OCT-1990	7: 5:57	611.08	2.241	2.103	6840.24	0.0652	75.5	136.2	147.5	252.2
31-OCT-1990	7: 8:25	659.17	4.531	0.901	7388.35	0.0494	86.0	144.9	30.8	4.0
31-OCT-1990	7: 9:20	776.96	10.794	1.216	8006.89	0.1080	76.9	138.7	35.0	0.7
31-OCT-1990	7:37:56	817.06	8.215	1.899	7792.90	0.0786	102.4	326.2	148.5	356.1
31-OCT-1990	7:52:20	658.06	2.319	1.344	6649.69	0.0562	87.8	339.9	324.4	180.8
31-OCT-1990	8:15:33	871.42	1.477	0.993	7476.38	0.0321	100.1	336.9	146.3	358.3
31-OCT-1990	8:21:55	808.98	6.160	1.014	6632.00	0.0817	78.1	157.4	216.0	179.6
31-OCT-1990	8:28:46	801.51	3.141	1.138	7610.40	0.0584	78.4	159.5	31.8	3.6
31-OCT-1990	8:56:20	485.76	0.339	1.367	7443.20	0.0796	100.3	181.9	36.4	359.2
31-OCT-1990	9:22:26	614.11	2.881	1.447	7305.91	0.0447	84.9	177.4	36.5	358.7
31-OCT-1990	9:47: 1	812.35	5.689	0.942	6694.19	0.0723	77.6	178.1	218.6	177.1
31-OCT-1990	9:53:37	619.39	9.757	2.640	6515.88	0.0720	83.1	184.0	218.0	176.9
31-OCT-1990	10: 5:56	621.96	9.709	1.376	7143.04	0.0222	84.0	15.9	155.3	349.8
31-OCT-1990	10:32:41	809.07	4.517	5.068	5113.14	0.4031	76.2	28.9	323.7	180.4
31-OCT-1990	10:41:22	803.07	5.253	2.525	7361.64	0.0267	75.2	31.0	154.2	350.0
31-OCT-1990	10:56:36	814.54	0.915	0.951	8176.20	0.1228	66.2	186.4	31.1	6.9
31-OCT-1990	10:57:14	797.83	12.415	0.987	6968.95	0.0279	76.6	34.5	328.9	175.0
31-OCT-1990	11: 3:59	716.67	2.130	1.687	7727.57	0.0847	99.9	213.6	25.1	9.5
31-OCT-1990	12:26: 0	597.91	3.335	2.506	7212.01	0.0348	82.4	221.7	28.7	6.4
31-OCT-1990	15:12:44	890.81	0.509	3.566	6484.91	0.1191	100.5	275.9	212.1	183.8
31-OCT-1990	15:14:43	916.85	4.148	0.984	7171.12	0.0161	74.7	100.2	307.7	196.2
31-OCT-1990	15:54:28	870.43	1.070	1.203	7151.87	0.0379	67.4	116.1	251.8	252.0
31-OCT-1990	16:18:20	465.99	2.300	2.082	5940.21	0.1500	49.5	248.7	228.4	180.4
31-OCT-1990	16:22:49	902.57	1.244	1.578	8002.71	0.0924	84.3	282.7	42.0	353.7
31-OCT-1990	17:16:38	678.29	0.306	1.207	6413.78	0.0982	51.0	265.3	225.3	182.4
31-OCT-1990	17:52:20	791.31	3.057	1.591	6593.89	0.0854	77.6	300.2	218.4	177.2
31-OCT-1990	17:56: 8	783.90	9.067	1.050	6025.53	0.1864	35.1	211.3	276.8	180.1
31-OCT-1990	18:40:51	914.78	1.887	1.550	6556.78	0.1105	84.6	145.0	321.7	183.6
31-OCT-1990	19:56:24	850.78	7.507	3.756	6836.54	0.0557	69.4	324.5	213.3	184.6
31-OCT-1990	20: 9: 6	585.49	5.215	3.157	5785.68	0.2014	84.8	339.7	215.8	179.1
31-OCT-1990	20:15: 3	789.47	10.578	1.279	7033.44	0.0172	107.9	151.8	320.2	183.0
31-OCT-1990	20:21:40	935.47	2.943	2.026	6551.15	0.1144	68.0	330.1	219.0	178.6
31-OCT-1990	20:57:35	879.97	0.918	1.024	6401.00	0.1493	42.0	225.7	325.7	152.3
31-OCT-1990	20:57:54	826.19	4.664	0.846	7136.62	0.0264	79.9	347.8	287.2	106.9
31-OCT-1990	21:28:21	918.58	5.667	1.432	8457.13	0.1388	100.2	10.0	35.0	0.5
31-OCT-1990	21:36:53	862.91	7.169	2.147	8835.28	0.1821	86.6	3.2	32.2	2.3
31-OCT-1990	21:58:48	658.97	3.534	1.529	7114.29	0.0128	85.1	193.8	138.7	6.2
31-OCT-1990	22: 3:39	787.76	6.128	1.363	7762.33	0.0785	101.0	19.9	35.1	0.5
31-OCT-1990	23:49:46	799.32	5.848	0.977	7993.70	0.1039	78.8	30.9	32.4	2.8
29-JAN-1991	5:14:26	795.20	7.957	1.296	7067.33	0.0132	78.9	36.8	321.3	183.2
29-JAN-1991	5:27:10	946.18	1.788	0.990	10306.33	0.2906	91.8	213.7	36.1	359.2
22-AUG-1991	16:54:23	786.63	5.107	1.244	6573.05	0.0880	78.3	217.2	215.3	180.3
22-AUG-1991	17:24:46	634.43	0.205	0.911	7721.59	0.0935	96.8	237.9	36.5	358.8
22-AUG-1991	17:27: 9	816.88	6.111	1.225	6528.93	0.1000	79.6	226.5	216.1	179.3
22-AUG-1991	17:28: 4	811.01	2.842	5.203	6615.97	0.0847	76.8	224.3	217.9	177.9
22-AUG-1991	17:56: 6	895.27	1.205	1.286	8630.47	0.1588	101.1	248.4	36.0	359.6
22-AUG-1991	18: 2:33	534.53	2.056	1.741	5783.74	0.1930	82.9	237.3	216.9	178.0
22-AUG-1991	18:33: 5	811.50	5.885	1.506	7820.48	0.0824	104.3	59.9	144.6	359.4
22-AUG-1991	20:11:12	846.07	0.743	5.895	6666.34	0.0840	107.4	82.4	335.7	166.6
22-AUG-1991	20:38:56	587.29	3.361	1.066	7591.81	0.0843	99.0	287.7	37.5	358.0
22-AUG-1991	21: 7:31	759.06	2.317	0.678	6248.36	0.1402	35.1	198.2	271.0	179.3
22-AUG-1991	21:44:51	802.65	4.353	1.369	7716.83	0.0712	84.5	121.9	142.3	2.5
22-AUG-1991	21:51:43	784.62	6.215	2.472	10500.49	0.3191	35.2	205.1	93.1	0.5
22-AUG-1991	0: 8: 4	834.25	49.257	0.739	7211.93	0.0020	72.0	320.9	7.7	29.2
22-AUG-1991	0:10: 0	636.57	6.832	0.990	7239.99	0.0329	86.7	332.0	33.6	1.3
22-AUG-1991	1:19:14	747.11	0.919	1.755	6074.75	0.1708	76.7	181.7	323.4	180.7
22-AUG-1991	2: 2:35	591.80	14.337	1.133	6377.79	0.0908	60.6	205.5	318.2	181.1

22-AUG-1991	2:19:52	855.16	0.411	0.844	8137.25	0.1128	100.2	14.1	37.7	358.0
22-AUG-1991	3:19:34	712.69	0.055	1.806	6136.69	0.1534	94.6	25.5	213.1	182.1
22-AUG-1991	3:24: 8	551.00	1.885	1.217	6203.62	0.1148	85.4	19.8	215.3	179.7
22-AUG-1991	3:35:27	834.89	0.393	1.515	6479.48	0.1116	69.8	11.1	222.0	174.9
22-AUG-1991	4:29:33	795.25	6.609	0.922	7190.70	0.0043	77.9	228.4	131.4	12.7
22-AUG-1991	4:31:10	717.66	3.330	3.736	5860.87	0.2086	35.2	305.6	275.3	178.0
22-AUG-1991	4:37:53	785.65	3.089	1.359	6859.79	0.0431	80.4	35.1	225.4	169.6
22-AUG-1991	6: 4:25	685.23	0.075	1.059	7426.45	0.0508	91.1	242.4	148.9	356.4
22-AUG-1991	7: 4:59	859.68	1.282	2.570	7087.58	0.0194	72.0	65.4	221.9	174.9
22-AUG-1991	7:13:23	869.98	2.808	1.223	6925.03	0.0463	85.0	76.9	201.0	194.6
22-AUG-1991	7:23:49	531.74	2.101	1.136	6586.47	0.0471	98.3	257.3	326.2	178.4
22-AUG-1991	8:25:57	711.57	2.020	1.521	6292.25	0.1247	35.5	358.4	279.8	178.5
22-AUG-1991	8:56: 6	652.25	6.987	1.111	6843.98	0.0259	86.7	104.3	227.0	167.6
22-AUG-1991	9:10:11	659.38	0.409	3.176	5421.32	0.2957	52.1	77.5	225.8	180.3
22-AUG-1991	10: 0:33	798.45	4.881	0.899	7114.77	0.0077	77.9	310.9	296.7	207.7
30-OCT-1991	19:28: 7	923.57	2.279	1.107	7985.10	0.0872	85.1	328.2	34.7	0.2
30-OCT-1991	20:12:40	783.37	1.163	1.786	8322.15	0.1411	98.4	349.1	33.5	1.5
30-OCT-1991	23:29:14	634.46	5.814	3.404	6033.94	0.1600	80.2	218.9	325.1	179.4
30-OCT-1991	1:19:22	572.88	3.860	4.160	11449.07	0.3940	89.2	59.6	34.0	0.5
30-OCT-1991	1:34:59	811.34	11.303	1.274	6888.86	0.0418	73.0	255.7	320.5	183.1
30-OCT-1991	2:42:52	766.42	0.520	4.093	22359.04	0.6814	48.1	299.3	134.2	358.6
30-OCT-1991	3:53:54	789.21	8.940	1.250	7678.97	0.0683	78.3	287.1	145.0	359.4
30-OCT-1991	4:20:11	640.25	0.671	0.825	8066.86	0.1464	107.3	272.7	173.3	334.2
30-OCT-1991	4:56:28	574.34	3.443	1.024	6265.50	0.1699	38.8	354.3	250.7	230.3
30-OCT-1991	5:32:36	703.15	1.546	3.237	8064.33	0.1865	54.0	333.5	78.2	48.1
30-OCT-1991	6:31:48	602.03	4.567	1.041	7084.11	0.0166	79.1	326.2	151.1	353.3
30-OCT-1991	6:34:28	923.53	1.474	2.782	10247.18	0.2887	71.7	125.9	36.6	0.3
30-OCT-1991	7: 3:57	953.17	5.221	1.005	6687.35	0.0944	71.7	132.7	214.7	182.6
30-OCT-1991	7:33:52	644.21	10.044	1.288	7228.06	0.0305	84.0	338.2	151.7	353.5
30-OCT-1991	7:49: 6	723.97	4.908	1.155	5532.54	0.2813	35.5	78.5	260.8	180.4
30-OCT-1991	8:35:40	798.60	2.316	2.917	5132.51	0.3960	84.7	352.7	323.7	181.9
31-OCT-1991	11:17:39	550.68	1.442	0.868	7790.61	0.1123	85.2	206.4	35.9	359.2
31-OCT-1991	13: 3:55	912.03	1.854	1.316	7006.78	0.0387	81.0	63.2	328.8	175.6
31-OCT-1991	13:10:38	786.68	4.031	1.090	6953.46	0.0285	78.7	66.4	323.2	181.3
31-OCT-1991	13:44:33	775.32	3.283	1.606	7933.55	0.1009	84.7	70.7	136.5	7.7
31-OCT-1991	14: 0:44	651.54	0.440	1.672	6586.20	0.0663	97.1	255.5	206.0	189.6
31-OCT-1991	15: 6:24	756.75	2.309	1.310	6377.83	0.1167	35.3	170.8	276.2	179.0
31-OCT-1991	15:40: 9	661.43	0.990	1.355	8142.31	0.1371	86.3	98.5	144.4	0.6
31-OCT-1991	16: 2:51	872.11	1.271	2.458	10446.77	0.3073	89.6	280.7	33.5	1.0
31-OCT-1991	17:46:24	794.91	2.289	3.186	7505.83	0.0462	79.4	300.1	30.9	4.4
31-OCT-1991	18:23: 6	668.29	1.750	1.240	6670.45	0.0648	35.6	238.0	229.6	212.9

Contents are follows:

Tracking Data Acquisiton Department

(NO.48 1996 JUNE.)

Space Debris Observing System Study-Ground
Technology for Ensuring Safety of Space Activities
Space Debris Orbit Assumption Test by MU Radar

What is Space Debris?

Fourty-years of space activities have yielded new knowledge and convenience for mankind by launching satellites. However, satellites abandoned at the completion of their missions and pieces of exploded spacecraft become space debris. That debris poses serious problems for future space activities. Most satellites and space debris fly in space at a speed exceeding than 7km/s, and an impact with an 1cm-diameter pieces of space debris is almost equal to a car crash at 60km.

At present, space agencies worldwide are studying possible effects of space debris on future space activities and developing appropriate measures to deal with it.

Outline of Test

NASDA's Tracking and Data Acquisition Department has conducted a space debris observing system concept study for the past two years to support future manned space missions, predict reentry of spacecraft into the atmosphere, and contribute internationally by cataloging space debris.

This study included the drafting of a future system development and operation plan, and an optical tracking experiment with the National Astronomical Observatory, together with the space debris orbit assumption test using the Middle and Upper Atmosphere Radar (MU Radar) of the Radio Atmospheric Science Center of Kyoto University.The MU Radar is operated by the Radio Atmospheric Science Center of Kyoto University. This test was conducted to determine the feasibility of tracking hypothetical debris (it was NASDA's satellite, MOS-1b.) using the MU Radar and obtaining an orbit decision figure.

Outline of MU Radar

The MU Radar was located in Shigaraki, Shiga Prefecture so it could be used not only by Kyoto University, but also by other research institutes at home and abroad. It is a large active phased array radar which can monitor atmospheric phenomena in the middle and upper atmosphere. The MU Radar transmits signal from 475 dipole antennas installed in a 103m-diameter circular site, and immediately directs a composite radiation beam in a designated direction.

Test Results

The test pre-calculated the path of the hypothetical debris (MOS-1b) flying over Shigaraki and transmitted a fixed beam to MOS-1b's two passing points in space at the observation elevation exceeding 60 degrees to measure its elevation, azimuth and distance based upon echoes from the satellite.

The existing method, which is used for operating a normal NASDA satellite, can not decide its orbit based upon these data, due to the very small quantity of observation data (for less than 20 seconds). For this reason, trial-and-error efforts were continued to investigate statistical processing methods until an appropriate decision method could be successfully established.

The test produced useful technical information on debris orbit assumption and know-how necessary for a future debris observing ground system (Figure below). In fiscal 1996, an orbit assumption test for space debris in geostationary orbit will be performed in the National Astronomical Observatory by applying this assumed logic for processing the debris optical tracking experiment data.

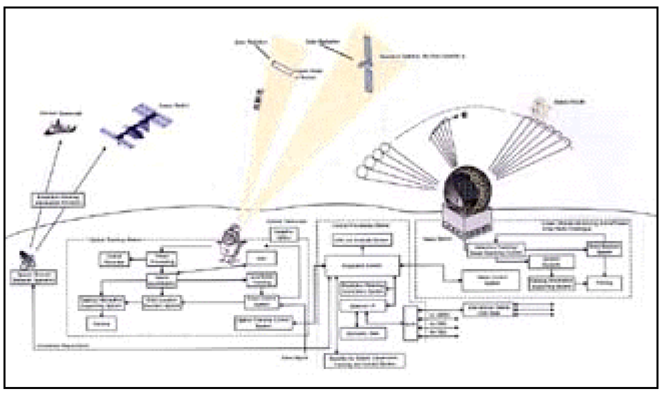


Figure.Space Debris Ground System Concept http://www-lab26.kuee.kyoto-u.ac.jp/~tsato/publ-text/esr.txt

Debris Observation with a VHF Radar

Radar has been the most effective means of observing LEO (low earth orbit) debris of `threatening size', which is larger than about 1~cm.

All existing data bases and statistics of such space debris, including the famous USSPACECOM catalogue, depend largely on observations with various radars.

They usually contain an important item `size', which is determined from the strength of the received echo.

In evaluating the impact of collision of debris with a shielding wall, for example, it is common to interpret it as the diameter of a sphere.

However, statistical studies showed that it is an overestimate by comparing the size estimated by radars with that calculated from the physical projected area determined from the orbital decay due to atmospheric drug[1].

What Do Radars See?

The size of the target is computed from the radar cross section (RCS), which is defined as the area of an isotropic scatterer whose echo power is the same as the given target.

It indeed agrees with the physical cross section for large metallic spheres, but often differs largely for objects with irregular shapes, especially when observed at a high frequency band.

For example, a piece of thin wire may be misinterpreted as a canon ball.

For objects smaller than the radar wavelength, RCS is proportional to the -4th power of the wavelength (or to the 4th power of the frequency). Most radars used for space debris monitoring thus employ a frequency of 5-10~GHz, or even higher, in order to obtain a high sensitivity against small debris.

At such a high frequency, the RCS varies drastically as the orientation of the target relative to the radar changes. It is then hard to estimate real cross section from the observed RCS.

The VHF MU Radar

At a lower frequency, on the other hand, the relation between the physical cross section and the RCS becomes much simpler, although we have to pay an expensive cost of the sensitivity reduction for small targets.

The MU (Middle and Upper atmosphere) radar of Kyoto University, Japan (Figure 1) is a powerful VHF radar operating at 46.5~MHz, whose 1~MW output power and the 100-m antenna size compensate for the reduced sensitivity at this frequency. It has roughly equal sensitivity as the radars used for USSPACECOM catalog maintenance[2].

The main target of this radar is the earth's atmosphere, or more precisely, weak backscattering from irregularities in the refractive index of the air caused by the atmospheric turbulence.

Since this atmospheric echo is so weak, scientists have been bothered by contamination of strong `undesired' echoes from various objects such as space debris. We decided to make use of these previously discarded echoes, and started a statistical study of space debris in 1988.

The antenna of the MU radar consists of 475 Yagi antennas constituting an active phased array. The advantage of this type of antenna is that it can observe different directions almost simultaneously by electronically switching multiple
antenna beams.

Figure~2 shows an example of debris observation using 8 antenna beams switched sequentially from pulse to pulse around the zenith[3]. The target, which turned out to be Kosmos 1023 rocket booster, passed through these beams, and the variation of RCS was tracked for about 20~sec.

It is also possible to roughly determine the orbit of the target from a single observation. Conventional radars with a large parabola antenna cannot continuously
observe an orbital object more than a fraction of a second unless its orbit is given beforehand.

The large and smooth variation of RCS versus time shown in the lower-right panel of this figure indicates the rotation of the rocket booster. The maximum value roughly agrees with its maximum physical cross section.

Estimating Shape of Debris

The most direct way to `see' the shape of a target using a radar is to make the antenna beam sharp enough so that it can resolve the target.

It is, however, impractical to get a resolution of 1~m at a distance of 100~km, because the necessary diameter of the antenna is the order of 10~km.

A more sensible technique is to make use of the rotation of the target. The idea is to resolve different part of a target moving at different velocity relative to the radar by measuring the Doppler velocity spectra. This method is called ISAR (Inverse Synthetic Aperture Radar), or RDI (Range-Doppler Interferometry), and has widely been used in military radars and in the radar astronomy.

It was already applied to space debris by using German FGAN radar, which revealed a clear image of a Salyut-Kosmos complex[4].

At the moment, the resolution is limited to about 1~m, so it cannot be used to identify the shape of small targets of 1--10~cm size, which is of the largest concern.

Some statistical information on the shape of space debris is obtained by comparing the physical cross section estimated from the atmospheric drag with RCS, as shown above.

The major limitation of this technique is that the same object has to be monitored for a long duration in order to orbital decay.

The results of our MU radar observations also provide similar information.

Numerical simulations showed that the magnitude of RCS variation can be interpreted in terms of the prolateness of the object. Since a single observation gives the variation seen from one direction, we need to interpret many observations in a statistical manner.

The result of such analysis indicates that the volume of relatively small debris observed with the MU radar is less than half of the sphere which has the same RCS.

Future Debris Radars

In order to evaluate the actual size of space debris, shape information must be obtained.

Although the first priority in designing a future debris radar is that it should have a sensitivity to detect objects of 1—10~cm, it also should have the capability of tracking an unknown object continuously for at least 10~sec, which is necessary to carry out both ISAR (RDI) analysis and/or the statistical analysis shown above.

The phased array antenna is the essential element in realizing this capability.

References

[1] G. D. Badhwar and P. D. Anz-Meador, Determination of the area and mass distribution of orbital debris fragments, {\it Earth, Moon, and Planets}, Vol.~45, pp.~29-51, 1989.

[2] T. Sato, H. Kayama, A. Furusawa, and I. Kimura, MU radar measurements of orbital debris, {\it J. Spacecraft}, Vol.~28, pp.~677-682, 1991.

[3] T. Sato, T. Wakayama, T. Tanaka, K. Ikeda and I. Kimura, Shape of space debris as estimated from RCS variations, {\it J. Spacecraft}, Vol.~31, pp.~665-670, 1994.

[4] D. Mehrholz, Radar tracking and observation of noncooperative space objects by reentry of Salyut-7/Kosmos-1686, {\it Proc. Internat. Workshop on Salyut-7/Kosmos-1686 Reentry}, No.~ESA~SP-345, pp.~1-8, 1991.

Toru Sato and Iwane Kimura
Graduate School of Electronics and Communication
Kyoto University

\item[Figure~1]
An aerial view of the MU radar, Shigaraki, Japan.

\item[Figure~2]
The angular motion (left), the height variation (upper right), and RCS variation (lower right) of Kosmos 0123 rocket booster as observed by the MU radar. Circles in the left panel show the coverage of the antenna beams.

http://www-lab26.kuee.kyoto-u.ac.jp/study/rg_e2.html

Study of space debris

Space debris is a name for undesired artificial objects left in space. It comprises unoperational satellites, launching rocket boosters, fragments of exploded rocket, exhausted solid propellant, etc. It has widely been realized that possible collision of operational spacecraft with such debris is getting to be a real threat for its safe operation.

Radar has been the most effective means of observing LEO (low earth orbit) debris of `threatening size', which is larger than about 1 cm. All existing data bases and statistics of such space debris, including the famous USSPACECOM catalogue, depend largely on observations with various radars. They usually contain an important item `size', which is determined from the strength of the received echo. In evaluating the impact of collision of debris with a shielding wall, for example, it is common to interpret it as the diameter of a sphere.

However, statistical studies showed that it is an overestimate by comparing the size estimated by radars with that calculated from the physical projected area determined from the orbital decay due to atmospheric drug.

What Do Radars See?

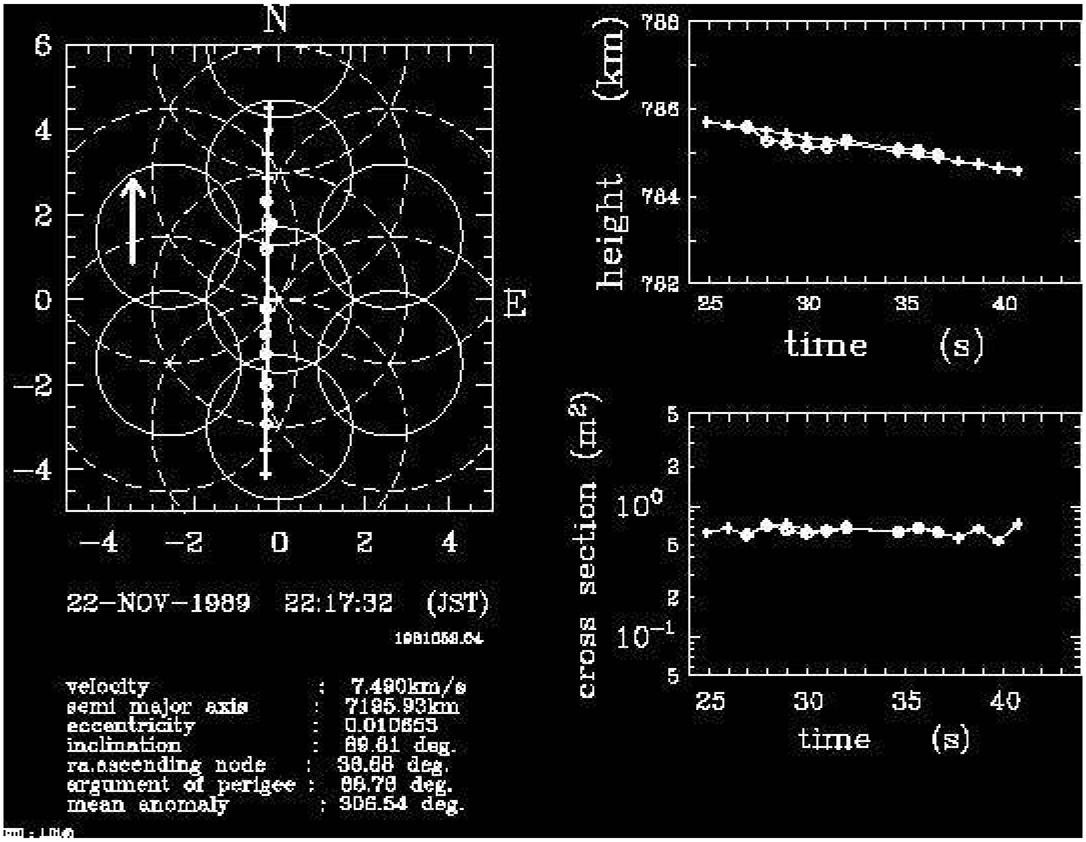
The size of the target is computed from the radar cross section (RCS), which is defined as the area of an isotropic scatterer whose echo power is the same as the given target. It indeed agrees with the physical cross section for large metallic spheres, but often differs largely for objects with irregular shapes, especially when observed at a high frequency band. For example, a piece of thin wire may be misinterpreted as a canon ball.

For objects smaller than the radar wavelength, RCS is proportional to the -4th power of the wavelength (or to the 4th power of the frequency). Most radars used for space debris monitoring thus employ a frequency of 5-10 GHz, or even higher, in order to obtain a high sensitivity against small debris. At such a high frequency, the RCS varies drastically as the orientation of the target relative to the radar changes. It is then hard to estimate real cross section from the observed RCS.

The VHF MU Radar

At a lower frequency, on the other hand, the relation between the physical cross section and the RCS becomes much simpler, although we have to pay an expensive cost of the sensitivity reduction for small targets.

The MU radar of Kyoto University, Japan is a powerful VHF radar operating at 46.5 MHz, whose 1 MW output power and the 100-m antenna size compensate for the reduced sensitivity at this frequency. It has roughly equal sensitivity as the radars used for USSPACECOM catalog maintenance.



[Observation of LCS4 satellite]

Statistical shape estimation of space debris

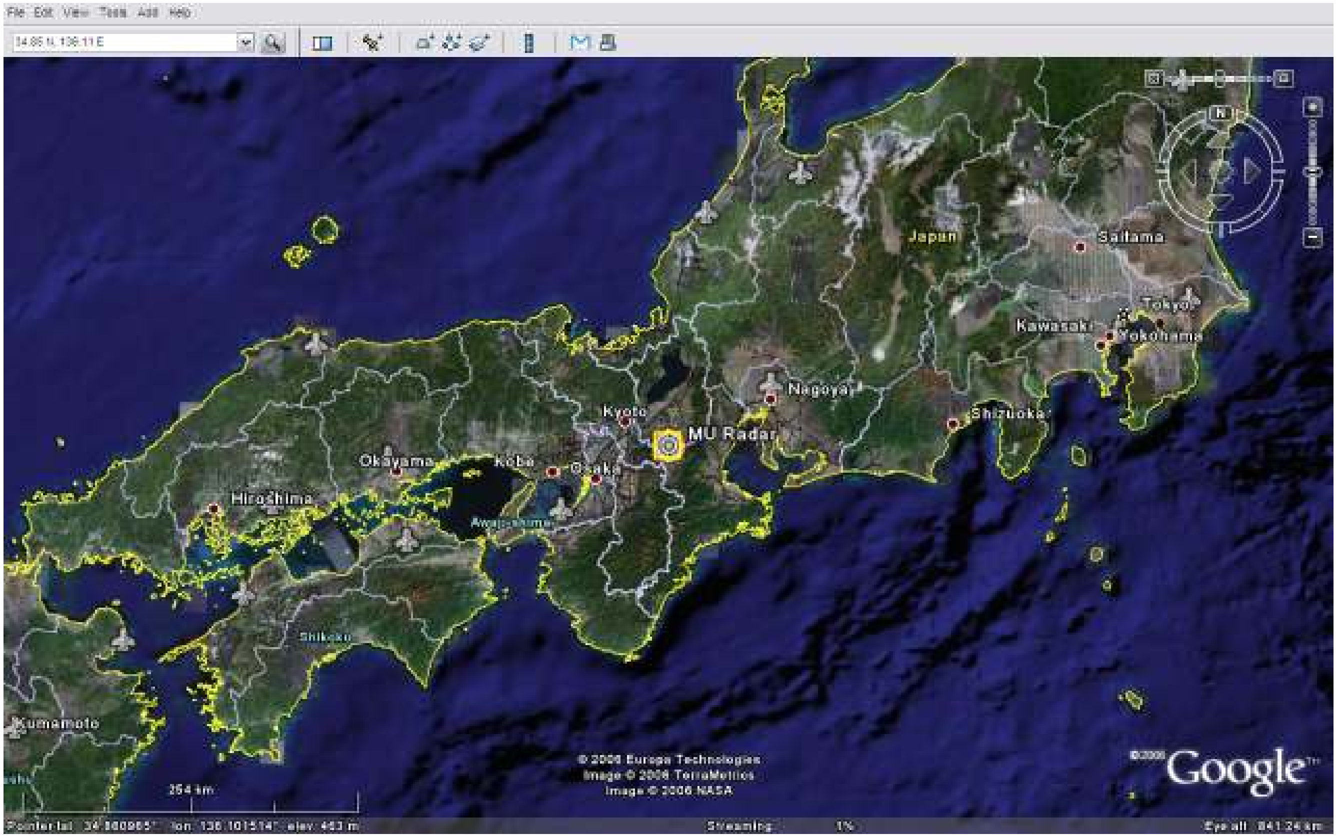
A special observation mode for space debris was developed for the MU radar in order to measure the time variation of the radar cross section (RCS). Since a simple low-frequency approximation holds for the analysis of scattering of the radar signal from most of space debris, it is feasible to estimate the effective axial ratio of each target from the magnitude of the observed RCS variations. Preliminary statistical study showed that debris with smaller RCS has larger RCS variations than larger debris, suggesting that they may have elongated shape rather than spherical shape as usually assumed in the impact estimation. A series of numerical simulations has shown that the volume of small observed debris is estimated to be less than half of that of a sphere with the same RCS.

http://orbitaldebris.jsc.nasa.gov/library/UN_Report_on_Space_Debris99.pdf

Table 1. Radar facilities for debris observation

Country	*Organization*	*Facility*	*Type*	*Primary operation mode*	*Configuration*	*Field of view*	*Wave-length (m)*	*Sensitivity (diameter) (m)*	*Status*
Germany	FGAN	TIRA	Dish	Mixed	Monostatic	0.5	0.23	0.02 at 1,000 km	Operational
Germany	MPIfR	Effelsberg	Dish	Stare	Bistatic with TIRA	0.16	0.23	0.009 at 1,000 km	Experimental
Japan	Kyoto University	MU radar	Phased array	Stare	Monostatic	3.7	6.4	0.02 at 500 km	Operational
Japan	ISAS	Uchinoura	Dish	Mixed	Bistatic	0.4	0.13	0.02 at 500 km	Experimental
Japan	ISAS	Usuda	Dish	Mixed	Bistatic	0.13	0.13	0.02 at 500 km	Experimental
Ukraine/Russian Federation	. .	Evpatoria	Dish	Stare	Bistatic	0.1	0.056	0.003 at 1,000 km	Developmental
United States	NASA/ NSF	Arecibo	Dish	Stare	Bistatic	0	0.13	0.004 at 575 km	One-time experiment
United States	NASA/ DoD	Haystack	Dish	Stare	Monostatic	0.1	0.03	0.006 at 1,000 km	Operational
United States	NASA/ DoD	HAX	Dish	Stare	Monostatic	0.1	0.02	0.05 at 1,000 km	Operational
United States	NASA	Goldstone	Dish	Stare	Bistatic	0	0.035	0.002 at 500 km	Operational
United States	DoD	TRADEX	Dish	Mixed	Monostatic	0.61/ 0.30	0.23/ 0.10	0.03 at 500 km	Operational

24. The MU radar of Kyoto University of Japan has observed the radar crosssection variation of unknown objects for a period of 20 seconds. A bistatic radar system of the Institute of Space and Astronautical Sciences (ISAS) of Japan has the capability to detect objects as small as 2 cm at an altitude of 500 km.


File Edit View Tools Add Help
Japan
Saitama
Tokyo
Kawasaki
Yokohama
Nagoya
Shizuoka
Kyoto
MU Radar
Okayama
Kobe
Osaka
Hiroshima
Awaji-shima
Shikoku
Kumamoto
254 km
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Image © 2006 NASA
Google
Streaming


File Edit View Tools Add Help
148 m
© 2006 Europa Technologies
Image © 2006 DigitalGlobe
Google
Streaming
100%

http://www.physics.uwo.ca/~whocking/p103/mu1b.jpg

Appendix A

A MU-derived radar in Indonesia

Title:
Equatorial radar system

Authors:
Fukao, Shoichiro; Tsuda, Toshitaka; Sato, Toru; Kato, Susumu

Affiliation:
AA(Kyoto University, Uji, Japan), AB(Kyoto University, Uji, Japan), AC(Kyoto University, Uji, Japan), AD(Kyoto University, Uji, Japan)

Publication:
(COSPAR, IAGA, SCOSTEP, et al., Plenary Meeting, 27th, Workshops and Symposium on the Earth's Middle Atmosphere, Espoo, Finland, July 18-29, 1988) Advances in Space Research (ISSN 0273-1177), vol. 10, no. 10, 1990, p. 151-154. (AdSpR Homepage)

Publication Date:
00/1990

NASA/STI Keywords:
ANTENNA DESIGN, ATMOSPHERIC SOUNDING, DOPPLER RADAR, EQUATORIAL ATMOSPHERE, INCOHERENT SCATTER RADAR, RADAR ANTENNAS, BLOCK DIAGRAMS, DATA ACQUISITION, PHASED ARRAYS, TRANSMITTER RECEIVERS

DOI:
10.1016/0273-1177(90)90022-R

Bibliographic Code:
1990AdSpR..10..151F

Abstract

A large clear air radar with the sensitivity of an incoherent scatter radar for observing the whole equatorial atmosphere up to 1000 km altitude is now being designed in Japan. The radar will be built in Pontianak, West Kalimantan, Indonesia (0.03 deg N, 109.29 deg E). The system is a 47-MHz monostatic Doppler radar with an active phased array configuration similar to that of the MU radar in Japan, which has been in successful operation since 1983. It will have a PA product of about 3 x 10 to the 9th W sq m (P = average transmitter power, A = effective antenna aperture) with a sensitivity of approximately 10 times that of the MU radar. This system configuration enables pulse-to-pulse beam steering within 20 deg from the zenith. As is the case of the MU radar, a variety of operations will be made feasible under the supervision of the radar controller. A brief description of the system configuration is presented.

Equatorial radar system

Shoichiro Fukao, Toshitaka Tsuda, Toru Sato and Susumu Kato
Radio Atmospheric Science Center, Kyoto University, Uji, Kyoto 611, Japan

Advances in Space Research
Volume 10, Issue 10 , 1990, Pages 151-154

Available online 23 October 2002.

Abstract

A large clear air radar with the sensitivity of an incoherent scatter radar for observing the whole equatorial atmosphere up to 1,000 km altitude is now being designed in Japan. The radar will be built in Pontianak, West Kalimantan, Indonesia (0.03°N 109.29°E). The system is a 47-MHz monostatic Doppler radar with an active phased array configuration similar to that of the MU radar in Japan, which has been in successful operation since 1983. It will have a PA product of 3 × 109 Wm2 (P = average transmitter power, A = effective antenna aperture) with a sensitivity of approximately 10 times that of the MU radar. This system configuration enables pulse-to-pulse beam steering within 20° from the zenith. As is the case of the MU radar, a variety of operations will be made feasible under the supervision of the radar controller. A brief description of the system configuration will be presented.

http://www.bom.gov.au/bmrc/wefor/research/twpice/Darwin_Nov_2004_meeting/S2/S2_Tsuda_Indonesian_sondes.pdf

Equatorial Atmosphere Radar (EAR) (June 2001)

Circular array of 560 Yagi antennas (110m in diameter)

EAR : a wind profiler radar operated on 47 MHz with the peak transmitting power of 100 kW.

Location: Koto Tabang, West Sumatra, Indonesia (0.20˚S, 100.32˚E)

3 elements Yagi antennas

http://center.stelab.nagoya-u.ac.jp/cawses2005/PDF/nakamura_takuji.pdf

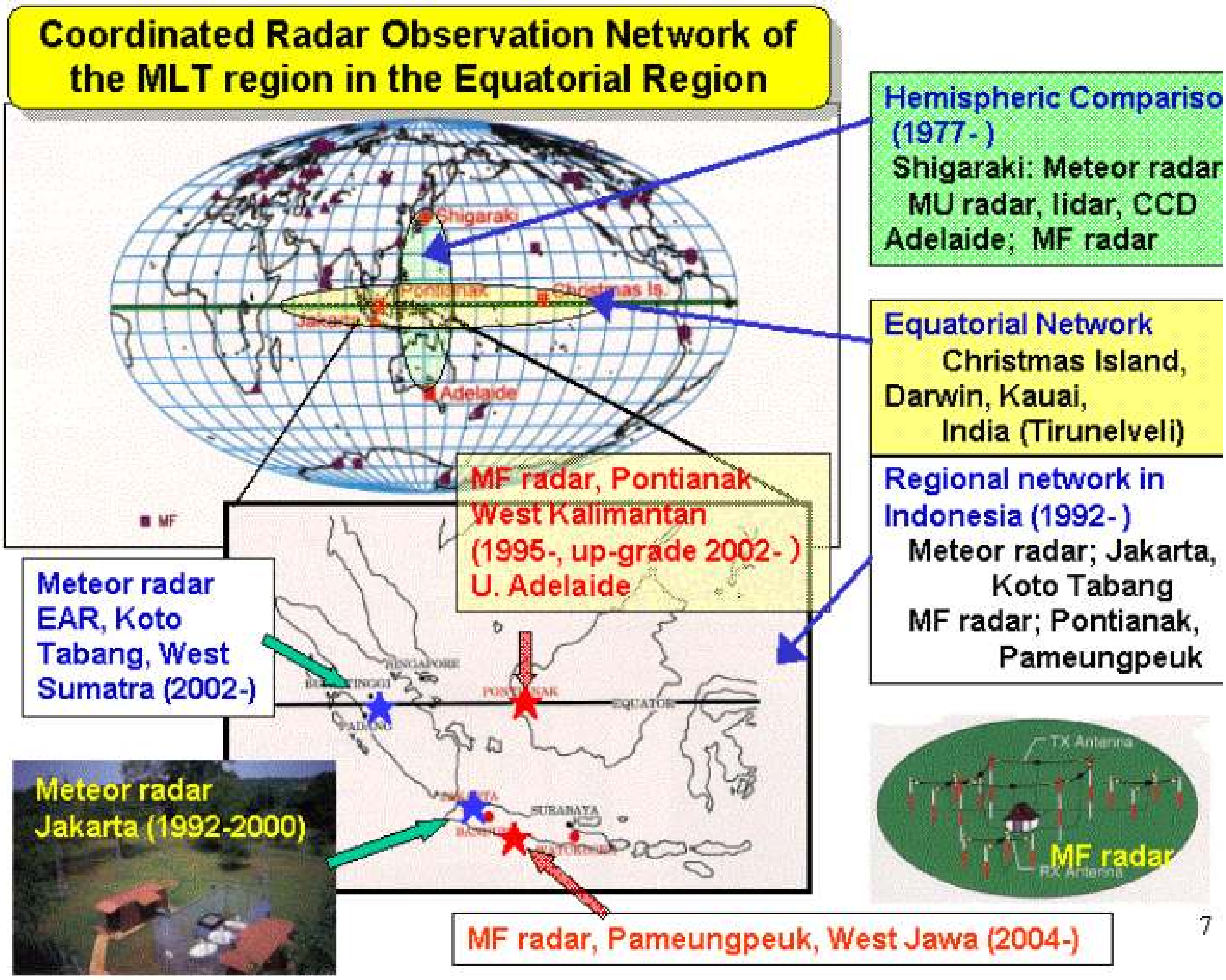


Figure 1 Location of MLT radar network in Indonesia

http://www.rish.kyoto-u.ac.jp/ear/index-e.html

Equatorial Atmosphere Radar (EAR)

Equatorial Atmosphere Radar (EAR)

EAR is a large Doppler radar built for atmospheric observation at the equator in West Sumatra in the Republic of Indonesia. It was completed in March 2001, a collaboration between the Research Institute for Sustainable Humanosphere (RISH), Kyoto University and the National institute of Aeronautics and Space of Indonesia (LAPAN).

The EAR has a circular antenna array of approximately 110 m in diameter, which consists of 560 three-element Yagis. It is an active phased array system with each Yagi driven by a solid-state transceiver module. This system configuration makes it possible to direct the antenna beam by electronic control up to 5,000 times per second.

The EAR transmits an intense radio wave of 47 MHz to the sky, and receives extremely weak echoes scattered back by atmospheric turbulence. It can observe winds and turbulence in the altitude range from 1.5 km to 20 km (troposphere and lower-stratosphere). It can also observe echoes from ionospheric irregularities at heights more than 90 km.

Specifications of the EAR

Location: 100.32E, 0.20S, 865 MSL
Frequency: 47.0 MHz
Output power: 100 kW (Peak envelope)

Antenna system: Quasi-circular active phased array (110 m diameter, 560 three-element Yagis)
Beam width: 3.4 deg. (Half power, one way)
Beam direction: Anywhere (within 30 deg. zenith angles)
Observation range: 1.5 km-20 km (Atmospheric turbulence), > 90 km (Ionospheric irregularity)

Research topics with the EAR

High-resolution observations of wind vectors will make it possible to study the detailed structure of the equatorial atmosphere that is related to the growth and decay of cumulus convection.

From long-term continuous observations, relationships between atmospheric waves and global atmospheric circulation will be clarified.

By conducting observations from near the surface to the ionosphere, it will be possible to reveal dynamical couplings between the equatorial atmosphere and ionosphere.

Based on these results, transports of atmospheric constituents such as ozone and greenhouse gases, and the variations of the Earth's atmosphere that lead to climatic change such as El-Nino and La-Nina, will be revealed.

History to the EAR

Study of atmospheric dynamics with the MU radar completed in 1984 in Shigaraki, Japan.

Cooperative study of equatorial atmosphere between RISH and institutes in Indonesia.
- PUSPIPTEK Radar Observatory operated by RISH and BPPT.
- MF Radar observations with RISH, LAPAN and University of Adelaide (Australia).
- Radiosonde observation campaign with RISH, LAPAN, and BMG.
- Cooperative feasible study for the EAR with RISH, LAPAN, and BPPT.

Note: BPPT: Agency for Assessment and Application of Technology, BMG: Meteorological and Geophysical Agency

Operations of the EAR

The EAR and the Observatory will be operated under international collaboration of scientists from Japan, Indonesia and other countries/areas.

The EAR will be the core facility of the atmospheric radar network around the equator operated by Japan, USA, Australia, etc.

The Observatory will expand by installing other instruments, i.e., radiosonde, lidar, etc.

Location of the EAR

Equatorial Atmosphere Observatory
Bukit Koto Tabang, Tromol Pos 16, Bukit Tinggi 26100, West Sumatra, INDONESIA

Jakarta-Padang: 2.0 h by air

Singapore-Padang: 1.5 h by air
Padang-Bukittinggi: 2.0 h by car
Bukittinggi-EAR: 1.0 h by car

http://www.rish.kyoto-u.ac.jp/English/EAR/index.html

京都大学生存圏研究所
Research Institute for Sustainable Humanosphere

Facilities of Cooperative Study Program:EAR,
Equatorial Atmosphere Radar

Overview

EAR is a large Doppler radar facility located at the equator in West Sumatra, Republic of Indonesia. It consists of 560 Yagi-antennas in a circular field of 110 m in diameter. EAR has almost the same functionality as the MU radar except that the output power is 100 kW. It can observe winds and turbulence in the altitude range of 1.5 km to 20 km (troposphere and lower-stratosphere), and ionospheric irregularities at an altitude above 90 km.

Photo: Antenna field of the EAR

In close collaboration with the National Institute for Aeronautics and Space (LAPAN) of Indonesia, EAR has carried out long-term observations since June 2001. Research funded by a Grant-in-Aid for Scientific Research for Priority Areas ``Coupling Processes in the Equatorial Atmosphere (CPEA)'' is currently being conducted during 2001-2006 as a collaborative study involving Shimane University, Tokyo Metropolitan University and Nagoya University. During the course of the CPEA projcet, various instruments have been accumulated in the EAR site.

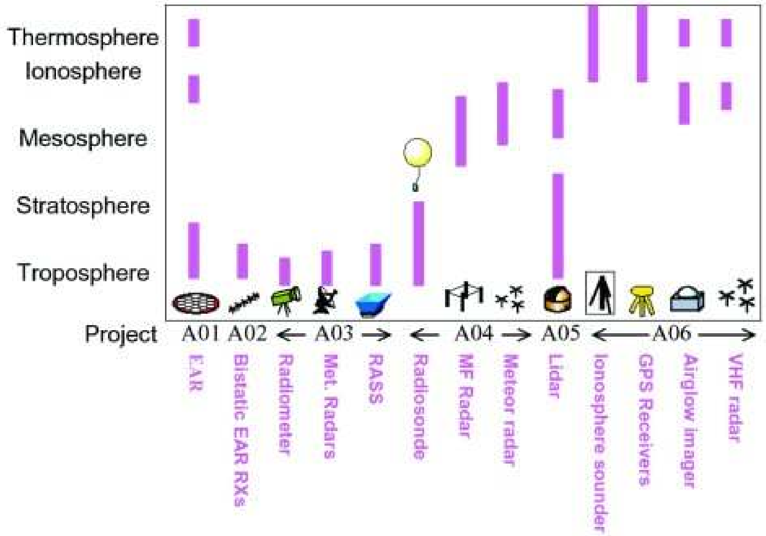


Figure: Various instrument in the EAR site

In addition to the EAR, we operate mediam frequency (MF) radar and boundary layer radar facilities in suburbs of Jakarta, West Kalimantan, South Jawa, which participate in a regional radar network in Indonesia, EAR, the MU radar and number of radar facilities in other countries forms international network of atmospheric radars around the equator.

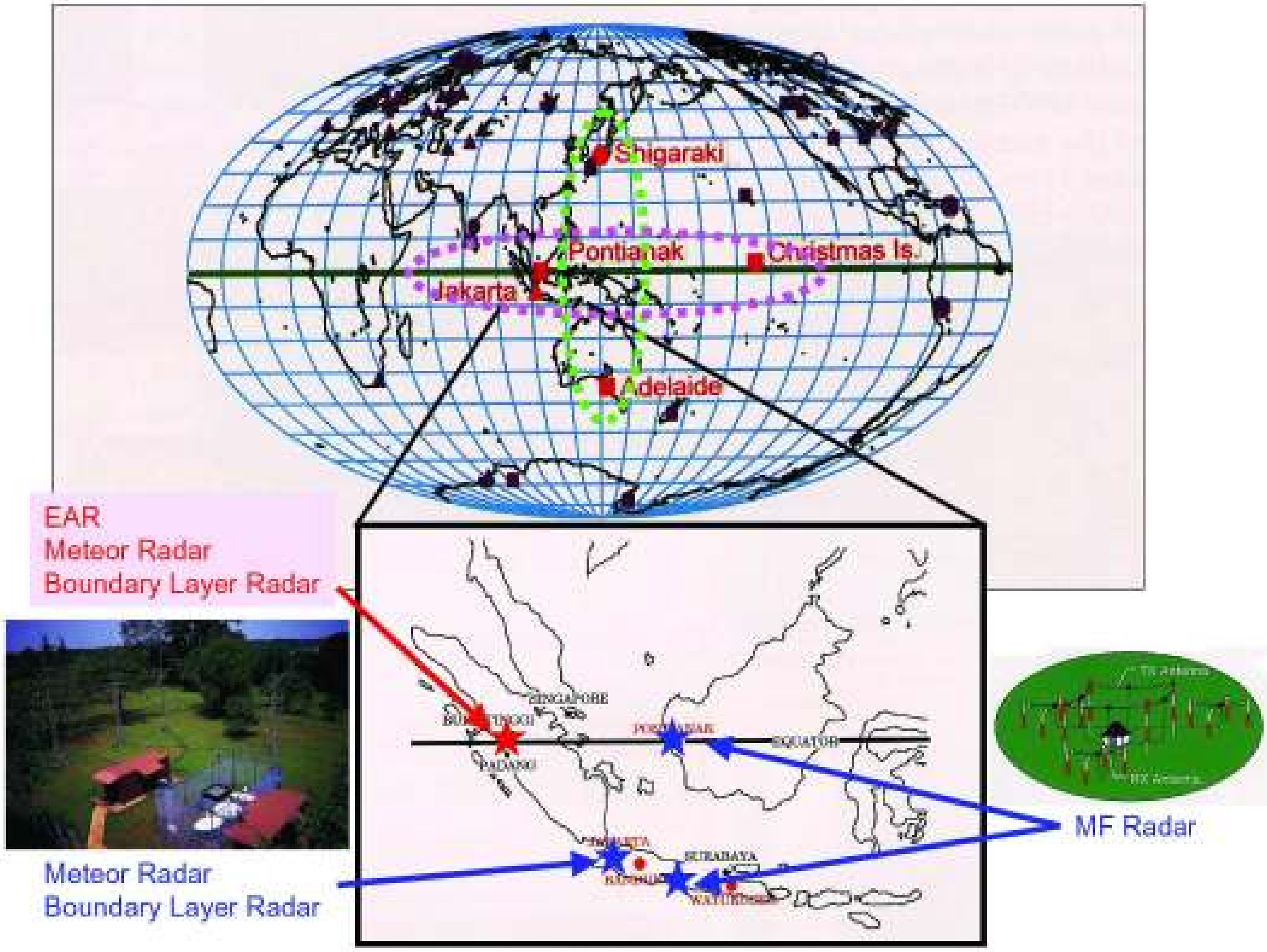


Figure: International network of atmospheric radars around the equator