

Rare examples of early VLF events observed in association with ISUAL-detected gigantic jets

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Received 19 August 2013; revised 4 December 2013; accepted 6 December 2013; published 8 January 2014.

[1] We examine narrowband VLF observations and investigate the association of early VLF perturbations with gigantic jets recorded by the Imager of Sprites and Upper Atmospheric Lightnings (ISUAL) instrument aboard FORMOSAT-2. From its inception in 2004 to April 2013, the ISUAL instrument has recorded 90 gigantic jets using a triggered camera. Stanford VLF receivers located around the world are used to detect perturbations to VLF transmitter signals associated with lightning. While nine gigantic jet events occurred within 100 km of a VLF transmitter-receiver great circle path, only four early VLF events were detected in association with three ISUAL gigantic jets. One of these is a moderate event of 0.4 dB amplitude change, and the others are very small. The recovery time of these events are less than a couple of minutes and so do not constitute the “long recovery” early VLF events that have been postulated to be associated with gigantic jets. We speculate on possible explanations for the lack of other events on monitored paths, including a lack of significant ionization produced in the *D* region ionosphere by the gigantic jet event, weak transmitter signals recorded by the receivers, or mode effects on transmitter paths.

Citation: Marshall, R. A., T. Adachi, R.-R. Hsu, and A. B. Chen (2014), Rare examples of early VLF events observed in association with ISUAL-detected Gigantic Jets, *Radio Sci.*, 49, 36–43, doi:10.1002/2013RS005288.

1. Introduction

[2] Gigantic jets (GJs) are the visible manifestation of upward discharges that result from electrical breakdown near the top of thunderstorms [Pasko *et al.*, 2002; Krehbiel *et al.*, 2008]. GJs expand upward from the cloud, initially similar to conventional lightning leaders, and transition to streamers before reaching the bottom of the ionosphere near 85 km altitude [Rioussel *et al.*, 2010]. They may be responsible for up to 2000 C km of charge moment change, and as such they may be an important component of the Earth’s global electric circuit [Cummer *et al.*, 2009]. The first GJs were observed from the ground by Pasko and Stenbaek-Nielsen [2002] and Su *et al.* [2003]; since then, only a handful of other observations of GJs have been made from the ground [e.g., van der Velde *et al.*, 2007; Lu *et al.*, 2011], and their occurrence rates are still not known.

[3] Far more GJs have been observed from space thanks to the Imager of Sprites and Upper Atmospheric Lightnings

(ISUAL) instrument [Chern *et al.*, 2003], launched aboard the FORMOSAT-2 satellite in 2004 with the goal of imaging sprites, halos, elves, and other Transient Luminous Events (TLEs). ISUAL uses a white-light intensified CCD imager, a six wavelength spectrophotometer, and two 16-channel array photometers to detect and measure TLEs. From 2004 to 2007, ISUAL recorded 5434 elves, 633 sprites, 657 halos, and 13 gigantic jets [Chen *et al.*, 2008], corresponding to global occurrence rates of 3.23, 0.5, 0.39, and 0.01 events per minute, respectively, for these four types of TLEs. As of April 2013, the number of GJs observed by ISUAL has increased to 90.

[4] Recent publications from ISUAL-detected GJs are further advancing the understanding of these events. Kuo *et al.* [2009] presented high time resolution measurements of GJs from ISUAL and were able to estimate the upward propagation velocity of $\sim 10^7$ m/s for the fully developed jet stage, as well as the reduced electric field in the vicinity of the GJ from spectral ratios. The reduced field of 400–655 Td significantly exceeds the conventional breakdown threshold of ~ 123 Td, suggesting that these GJs be associated with significant new ionization. Lee *et al.* [2012] make the distinction between secondary jets and secondary gigantic jets in ISUAL data. These “secondary jets” are identical to the “secondary TLEs” of Marshall and Inan [2007] or “palm trees” of Heavner [2000]; the advancing scientific understanding of these events appears to be leading to a more descriptive name.

[5] Ground-based observations of GJs have also recently been reported and are furthering the description of GJs.

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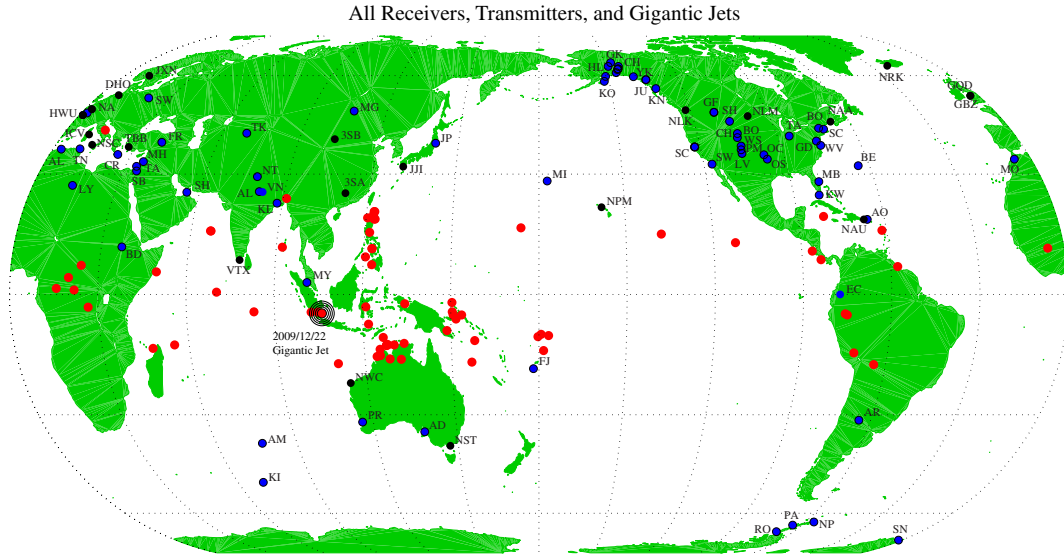


Figure 1. AWESOME VLF network receiver locations (blue dots), ground-based VLF transmitters monitored by the AWESOME VLF network (black dots), and ISUAL gigantic jets (red dots) from 2005 to 2012. The gigantic jet event from 22 December 2009 shown in Figure 5 is highlighted.

Soula et al. [2011] reported three GJs produced by an isolated thunderstorm near Réunion Island in the Indian Ocean. These were shown by ELF sferic waveforms to move negative charge from the cloud toward the ionosphere. *Lu et al.* [2011] provided a detailed description of the charge structure in the cloud at the time of two GJs observed near lightning mapping arrays. They also found lightning mapping array pulses from the GJ itself during its development, indicative of the leader-to-streamer transition near 35 km altitude. *Meyer et al.* [2013] studied the meteorological conditions around a number of GJs and found a possible link between convective surges and overshooting tops and the occurrence of gigantic jets. *van der Velde et al.* [2010] reported on a very bright GJ observed in Italy and showed using sferic waveforms that the GJ transferred negative charge from the ionosphere to the cloud, opposite to that of *Soula et al.* [2011]. In addition, a large 2 dB early VLF perturbation was detected with this GJ, but due to a near-simultaneous sprite, it is unclear whether the event is a long-recovery type.

1.1. Subionospheric VLF Remote Sensing

[6] Ground-based VLF transmitter signals propagate efficiently in the Earth-Ionosphere waveguide for tens of megameters (Mm). Stanford uses a network of low-noise VLF receivers to monitor these VLF transmitter signals, measuring variations in the amplitude and phase of each detectable signal. Lightning is known to perturb these signals [e.g., *Inan et al.*, 1995], and these perturbations have been attributed to heating and ionization in the D region of the ionosphere above the thunderstorm. These perturbations have come to be known as “early VLF” events [*Haldoupis et al.*, 2006] to distinguish them from the time-delayed lightning-induced electron precipitation events [e.g., *Inan et al.*, 1985]. Early VLF events have been associated with sprites and halos [e.g., *Inan et al.*, 1995; *Moore et al.*, 2003; *Marshall et al.*, 2006] and with elves [*Mika et al.*, 2006; *Marshall et al.*, 2006]. *Marshall et al.* [2010] found that early VLF events are unlikely to be associated with

single elve events because very little ionization is produced compared to that associated with sprite halos. However, *Haldoupis et al.* [2012] show a correlation between long recovery events and extremely large peak current lightning and elves.

[7] Early VLF events usually reach their perturbation maximum very quickly, within the 20 ms time resolution of the narrowband VLF data (“early/fast”), but sometimes

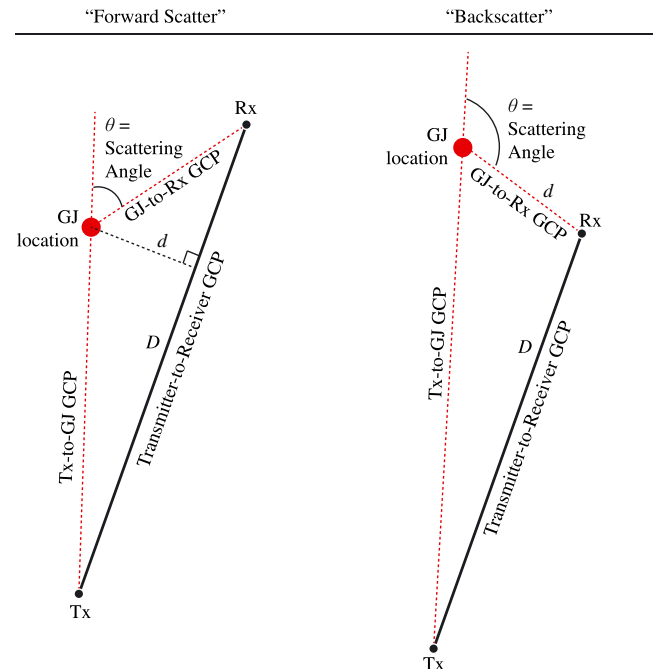


Figure 2. VLF scattering geometries for forward scattering (left) and backscatter (right). Backscatter is here defined as any case where the transmitter-to-GJ great-circle-path is longer than the transmitter-to-receiver path.

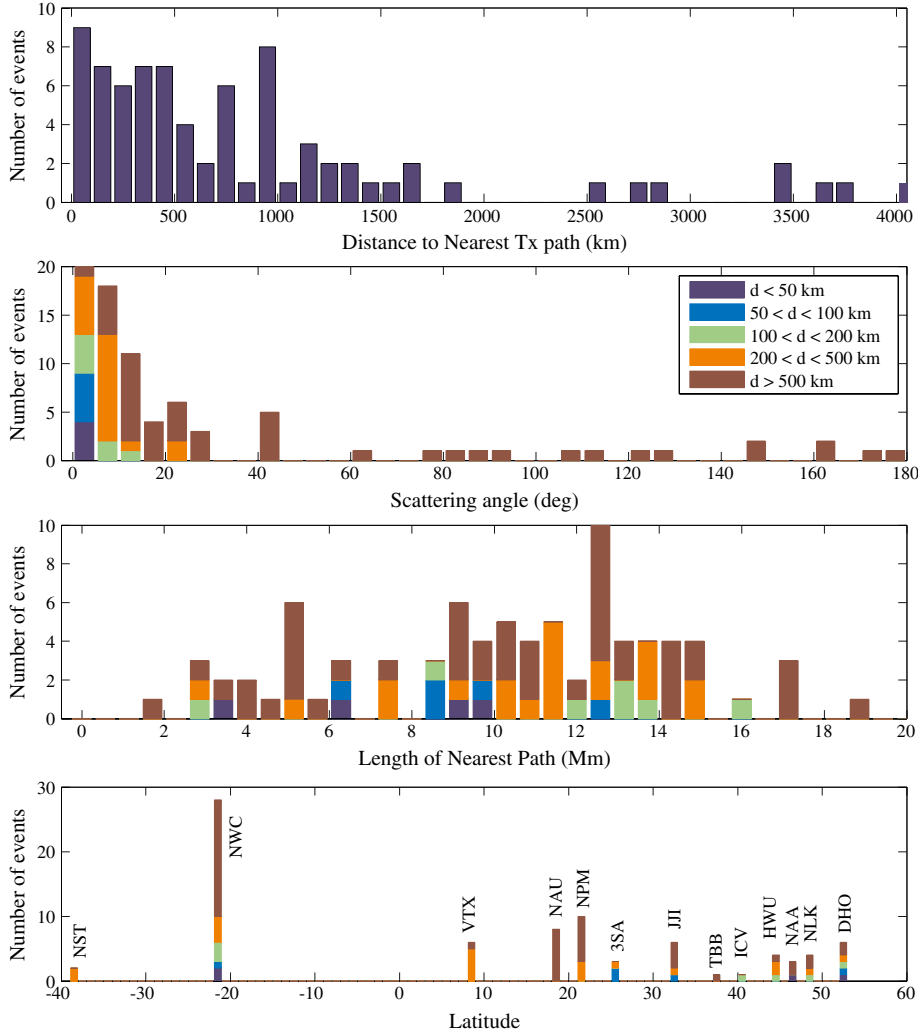


Figure 3. Histograms of VLF receiver-transmitter great-circle-paths associated with ISUAL-detected gigantic jets. See the text for detailed descriptions of the histograms.

they take up to 3 s to reach their maximum (“early/slow”) [Haldoupis et al., 2006]. They typically recover to ambient levels in 1–2 min, however, as expected from the recombination times at 80–90 km altitude to which the VLF subionospheric remote sensing method is most sensitive. *Cotts and Inan* [2007] reported the discovery of “long recovery” (LR) early VLF events, where the perturbation reaches its maximum quickly, but takes minutes and sometimes hours to recover back to ambient levels. *Lehtinen and Inan* [2007] attributed this long recovery to persistent ionization at lower altitudes (<60 km), possibly associated with gigantic jets, since halos and elves cannot produce ionization at those low altitudes.

[8] Recent work, however, has shown that LR events are connected to very large (>200 kA) peak current cloud-to-ground (CG) lightning, leading to a connection with elves [Haldoupis et al., 2012, 2013; Salut et al., 2013]. Since GJs are not associated with high peak-current lightning, these results suggest that GJs may not be associated with LR events. In this paper, we investigate the occurrence of any type of early VLF perturbations (early/fast, early/slow, and LR) in association with GJs observed by ISUAL.

2. Narrowband VLF Observations

[9] During the period of ISUAL observations from 2004 to 2012, the Stanford VLF group operated over 50 VLF receivers at locations covering all seven continents. The blue dots in Figure 1 show all of the Stanford receiver locations during this time period; note that not all of these were operating during the entire 9 year period. The black dots in Figure 1 show the ground-based VLF transmitters that are monitored. These vary in radiated power from tens of kW to 1 MW and in frequency from 10 to 40 kHz. Not all transmitters are monitored by all receivers; each receiver is set up to monitor those transmitters whose signal is detectable above the local noise floor. Nonetheless, a map showing great-circle-path (GCP) links between transmitter-receiver pairs for those that are monitored results in an incomprehensible image of overlapping lines.

[10] Instead, we create maps that are pertinent to each ISUAL-observed GJ. This involves a query of our VLF database to identify those receivers that were operating at the time of each GJ and to identify the transmitters that were monitored by those receivers at that time. For each transmitter-receiver pair we calculate the great-circle-path

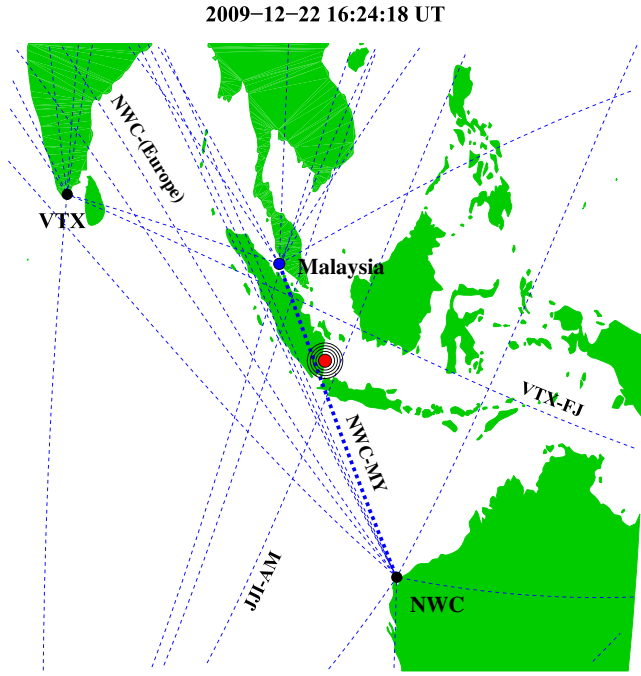


Figure 4. Gigantic jet event observed by ISUAL on 22 December 2009 and its relationship to VLF receivers, transmitters, and GCPs in the Southeast Asia region.

(GCP), the distance between the GCP and the GJ event, as reported by the ISUAL team and the “scattering angle” from transmitter to GJ to receiver. For instance, if the GJ lies directly on the GCP, the scattering angle is 0° (i.e., forward scattering). Figure 2 shows the geometry and relevant parameters, for an event along the GCP (forward scatter) and an event beyond the receiver (backscatter). The latter case is defined when the transmitter-to-GJ GCP is longer than the transmitter-to-receiver GCP. The length of the nearest GCP is denoted D , and the minimum distance from the GJ to the GCP is denoted d . In the backscatter case, d is exactly the GJ-to-receiver GCP.

[11] Note that the timing accuracy of ISUAL GJs is given by the ISUAL trigger time, offset by the propagation time for photons from the GJ to the instrument (10 ms for a GJ 3000 km distant) as well as the clock drift for the ISUAL instrument (tens of millisecond). For identification of early VLF events, we require only 1 s timing accuracy, so the ISUAL timing is more than sufficient to correlate with VLF data.

2.1. Summary of Events

[12] Figure 3 shows histograms summarizing the narrow-band data associated with all of the GJ events detected by ISUAL. The topmost histogram shows the distance from the GJ event to the nearest transmitter-to-receiver GCP. Clearly, if early VLF events associated with GJs are due to forward scattering, similar to sprite-associated early VLF events, they must be within 10 to 100 km from a path. Here we see that only nine events are within 100 km of a receiver-transmitter GCP and another seven are between 100 and 200 km. For sprites, *Johnson and Inan* [2000] and others have shown that early VLF events are usually observed only if the causative discharge is within ~ 50 km of the GCP. The second panel shows the scattering angle between the transmitter-to-GJ and GJ-to-receiver GCPs. Direct, forward scattering is 0° ; if the GJ is directly beyond the receiver, the scattering is 180° , denoting backscatter. The scattering angle is color coded by distance to path from the first histogram; clearly, events closest to paths have near-zero scattering angles. The third histogram shows the length of the nearest path for each event. Typically, early VLF events in the continental U.S. are detected on paths from 3000 to 5000 km, sometimes longer; similar path lengths are used in Europe [see, e.g., *Haldoupis et al.*, 2004]. Extremely long paths would be unlikely to show early VLF events, simply because the SNR is low, due to signal attenuation and spreading the Earth-ionosphere waveguide.

[13] Finally, the fourth histogram shows which transmitters are found to have the “nearest path” in the histograms above; they are shown by latitude for convenience but labeled with call signs. The NWC transmitter is most often used in this analysis; this is not surprising since a large fraction of the GJ events are in Southeast Asia, and there are

Table 1. Gigantic Jet Events Closest to Transmitter-Receiver Great-Circle-Paths

Date/Time	Jet Latitude	Jet Longitude	Tx	Rx	GCP Length (km)	Distance to GCP (km)	Scattering Angle (deg)
2008 Jan 01 15:08:39	15.2°S	124.2°E	NWC	Midway (MI)	9,238	25	1.0
2008 May 01 16:51:22	11.5°N	92.1°E	NWC	Allahabad (AL)	6,349	56	2.2
			NWC	Varanasi (VN)	6,225	59	2.3
2009 Apr 04 16:27:29	4.3°S	102.5°E	NWC	Allahabad (AL)	6,349	55	1.9
			NWC	Tashkent (TK)	8,413	59	1.6
			NWC	Varanasi (VN)	6,225	12	0.3
2009 Aug 14 14:46:11	18.4°N	123.1°E	NRK	Adelaide (AD)	16,503	124	0.6
			NLK	Amsterdam (AM)	18,088	85	0.2
			3SA	Fiji (FJ)	8,646	63	2.8
2009 Aug 14 14:46:34	18.5°N	122.7°E	NLK	Amsterdam (AM)	18,088	115	0.3
			3SA	Fiji (FJ)	8,646	89	3.6
2009 Sep 12 14:45:44	18.7°N	120.4°E	JJI	Amsterdam (AM)	9,549	72	2.3
2009 Dec 22 16:24:18	4.6°S	106.1°E	NWC	Malaysia (MY)	3,096	121	10.0
2010 Nov 25 22:02:16	42.2°N	14.7°E	HWU	Sde Boker (SB)	3,361	18	1.1
2011 Mar 22 20:03:45	13.2°S	47.4°E	DHO	Kerguelen (KI)	12,804	73	0.9
2012 Sep 03 03:00:25	22.1°N	60.7°W	DHO	Ecuador (EC)	9,765	11	0.2

Table 2. Gigantic Jet Events With Shortest (< 5000 km) Transmitter-to-Receiver Great-Circle-Paths

Date/Time	Jet Latitude	Jet Longitude	Tx	Rx	GCP Length (km)	Distance to GCP (km)	Scattering Angle (deg)
2009 Aug 14 14:46:11	18.4°N	123.1°E	JJI	Malaysia (MY)	4484	603	31.3
2009 Aug 14 14:46:34	18.5°N	122.7°E	JJI	Malaysia (MY)	4484	572	29.6
2009 Dec 22 16:24:18	4.6°S	106.1°E	NWC	Malaysia (MY)	3096	121	10.0
2010 Sep 27 16:46:31	23.7°N	91.2°E	3SA	Allahabad (AL)	3071	257	21.0
			JJI	Allahabad (AL)	4863	505	35.1
2010 Nov 25 22:02:16	42.2°N	14.7°E	HWU	Sde Boker (SB)	3361	18	1.1 ^a
2012 Jul 20 04:38:49	6.8°N	79.4°W	NAU	Ecuador (EC)	2410	482	52.2
2012 Sep 03 03:00:25	22.1°N	60.7°W	NAU	Ecuador (EC)	2410	797	160.6

^aSee text for an explanation of the event.

a large number of paths emanating from NWC through that region. Note that while this histogram shows the nearest path to each GJ event, often a number of other paths also pass within a few hundred kilometers of the GJ event (e.g., see Figure 4).

[14] Tables 1 and 2 summarize the “best” events as far as early VLF event detection. Table 1 shows data for those GJ events that fall within 125 km of a GCP. We observe that only two of these events occur on GCPs shorter than 5000 km. This means that the transmitter signal is very weak at the receiver and thus has very low SNR. Conversely, Table 2 shows data for the eight GJs whose nearest GCP is shorter than 5000 km. Of these, only two fall within 125 km of the GCP. (Note: for the event shown in Table 2, footnote a, in addition to HWU, paths to Sde Boker for this event from DHO, GQD, ICV, NRK, and NSC range from 2101 to 3918 km; the GJ event falls from 18 to 713 km from the paths, with scattering angles from 1.1 to 106°. However, only GQD showed a perturbation, as shown in Table 3.)

[15] These histograms and tables demonstrate that of the 90 events detected by ISUAL, only a few could be expected to produce early VLF events, under the assumption of forward scattering. This is despite the global network of VLF receivers and transmitters and criss-crossing great-circle-paths. Simply put, the requirements of the event falling within ~ 100 km of a <5000 km long path are still too stringent given the small number of GJ observations from ISUAL. A vastly more dense network of VLF receivers would be required to provide statistically significant coverage of ISUAL-observed GJ events.

2.2. Early VLF Events

[16] Table 3 summarizes those GJ events for which an early VLF perturbation is observed. Note that the first two

events listed are the same GJ, with early VLF perturbations recorded by two different receivers. The VLF data and the optical data from ISUAL for this first event are shown in Figure 5. The GJ occurred over Southeast Asia at 16:24:18 UT (00:24:18 local time) on 22 December 2009, and the 0.4 dB perturbation is clearly observed on the NWC-to-Malaysia GCP. There is also a clear phase perturbation of about 2°. Due to the high variability of the signal amplitude and phase at the time of the event, the recovery time is difficult to ascertain, but it does not have the characteristics of the long recovery events reported by *Cotts and Inan* [2007]. Note that this event occurred 121 km from the GCP, resulting in a relatively wide scattering angle of 10.0°. A small perturbation of about 0.2 dB was also observed on the NWC-Nainital GCP at this time; this is a much longer GCP, and the GJ is 333 km from the GCP. The GJ event observed by ISUAL is classed as a bright “type I” GJ, as defined by *Chou et al.* [2010]. This event also produced a significant ULF signal at the NCKU ULF station some 3513 km away. The ULF signature may be evidence of current within the GJ but may also be accounted for by a nearby CG lightning discharge at the same time.

[17] Two other very small perturbations were found for GJ events from ISUAL; these and the first event observed on the NWC-Nainital path are shown in Figure 6. Both of these are barely distinguishable above the noise on very weak transmitter signals, and recovery times cannot be ascertained. Furthermore, we cannot rule out that these events are caused by other lightning near the GCP at the same time as the GJs but outside the field-of-view of ISUAL. In particular, the event on 25 November 2010 had a bright secondary event (probably a sprite) within 100 ms of the GJ initiation. At this time resolution it is impossible to determine if the early VLF perturbation corresponds to the GJ or the secondary event. This event may be a sprite or halo; in addition, there is a brightening of the cloud below the GJ, which may be a new lightning return stroke. The other three

Table 3. Gigantic Jet Events Coincident With Early VLF Perturbations

Date/Time	Jet Latitude	Jet Longitude	Tx	Rx	GCP Length (km)	Distance to GCP (km)	Scattering Angle (deg)	Pert. Amp. (dB)
2009 Dec 22 16:24:18	4.6°S	106.1°E	NWC	Malaysia (MY)	3,096	121	10.0	0.4
			NWC	Nainital (NT)	6,821	333	12.1	0.2
2010 Nov 25 22:02:16	42.2°N	14.7°E	GQD	Sde Boker (SB)	3,918	338	19.1	0.1
2011 Jan 12 04:37:43	17.2°S	64.1°W	NAA	Palmer (PA)	12,168	195	2.5	0.1

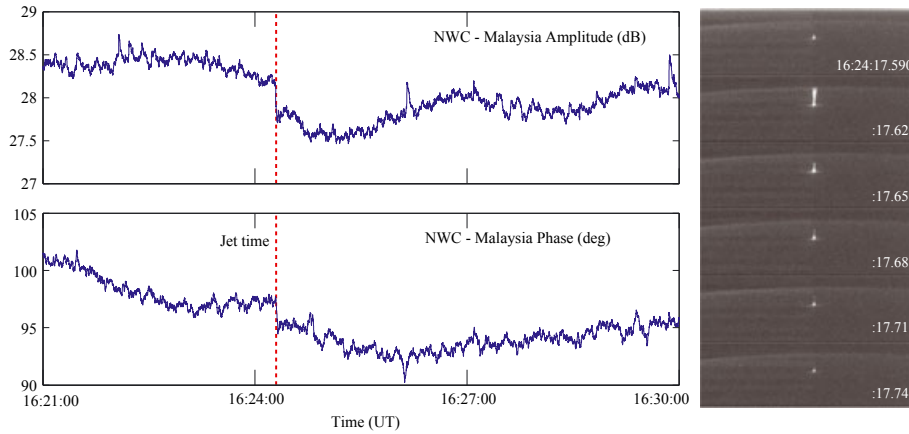


Figure 5. Early VLF event observed simultaneous with the gigantic jet event on 22 December 2009, on NWC-Malaysia path. ISUAL images of the GJ itself are shown at right.

events did not have near-coincident sprites or halos in the ISUAL field-of-view. The GJ at this time was a much less bright “type III” event [Chou *et al.*, 2010], and no ULF signature was observed at the NCKU station, in this case 9537 km away.

[18] While this paper focuses on GJ events observed by ISUAL, we have also found VLF narrowband data at the

time of the three GJs observed over Réunion Island reported by Soula *et al.* [2011]. At the time of these events, data were recorded at Kerguelen Island in the South Indian Ocean; the GCP from the DHO transmitter in Germany passed 546 km from the GJ events, for an 8.9° scattering angle, but the GCP is over 12,000 km. No early VLF perturbations were observed.

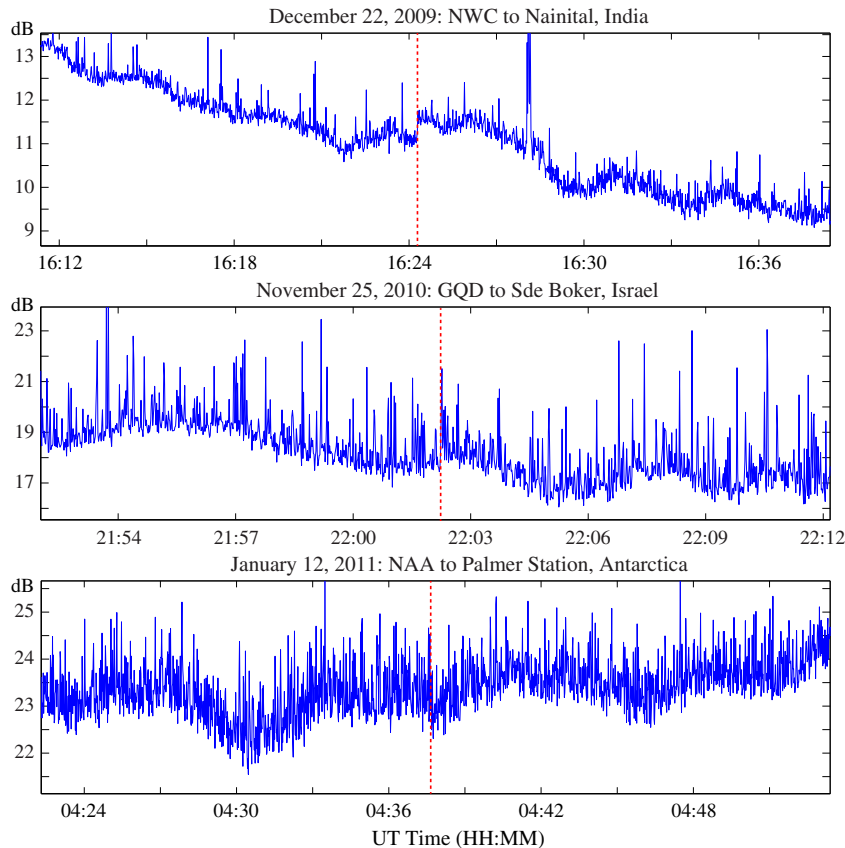


Figure 6. Three early VLF events observed on transmitter-to-receiver paths as shown. In all cases, the perturbation is less than 0.1 dB and the recovery time cannot be determined.

3. Discussion

[19] The data presented here show that only three of 90 gigantic jets observed by ISUAL coincided with early VLF perturbations observed on Stanford's global network of VLF receivers. Of these, only one (Figure 5) had a clear and prominent perturbation of greater than 0.2 dB amplitude change. The paucity of coincident events can be attributed to either (a) GJ events falling far from great circle paths, so that forward scatter cannot be observed; (b) GJ events falling near very long GCPs, so that the signal-to-noise ratio of the detected signal is very low; or (c) GJ events occurring without early VLF perturbations due to a lack of ionization produced in the lower ionosphere by the event.

[20] Clearly, many of the ISUAL GJs fall under categories (a) and/or (b) above. However, the tables and histograms herein demonstrate that at least a few events had reasonable length paths (<5000 km) and fell near enough to the GCP to expect forward scattering. In these cases, it is possible that the GJ event (or its causative lightning event) did not produce sufficient ionization to yield an early VLF event. It is also possible that in some cases an ionospheric disturbance was produced, but a perturbation is not observable on the transmitter signal due to inopportune placement of the disturbance on the GCP: due to mode interference in the Earth-ionosphere waveguide, large disturbances can result in zero-amplitude perturbations at multiple locations along the GCP [e.g., Marshall and Inan, 2010].

[21] Considering the recovery signature of the large early VLF event in Figure 5, it is clear that while the recovery time cannot be easily established from this data, qualitatively, it would appear that the recovery time is no more than 3 min, i.e., the amplitude change will have recovered back to the ambient level by 16:27:00 UT. In this case, this would not be considered a long recovery event. This "traditional" early VLF event therefore runs counter to the postulate of Lehtinen and Inan [2007] that long recovery events are due to persistent ionization at low altitudes associated with gigantic jets. However, further observations of GJs with coincident VLF data are needed to clearly prove or disprove this hypothesis.

[22] Recent work [Salut et al., 2013; Haldoupis et al., 2013] has made a case that long recovery events are not due to GJ-related ionization but rather to extremely large peak current lightning. The authors show that long recovery events are found to be predominantly caused by >150 kA peak current lightning. This high-peak current lightning would very likely also produce elves, but there is no peak current dependence for GJs. The physical mechanism that produces the persistent ionization responsible for long recovery events is not yet known, but the correlation is clear.

[23] **Acknowledgments.** R. Marshall acknowledges support from NSF CEDAR Postdoctoral Award AGS-1027070, NSF grants ATM-0551174 and PLR-1043442, and ONR grant N00014-0-90443. T. Adachi acknowledges support from JSPS grant 24840040 and Waseda University grant 2012A-933. We thank the large array of host institutions for supporting the Stanford AWESOME VLF receiver network across the globe.

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