IRIDIUM SATELLITE SIGNALS: A CASE STUDY IN INTERFERENCE CHARACTERIZATION AND MITIGATION FOR RADIO ASTRONOMY OBSERVATIONS

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INTRODUCTION

Some sources of radio frequency interference (RFI) are inescapable. While radio astronomers can minimize the effects of many terrestrial sources by placing their telescopes at remote sites, none can escape from RFI generated by satellite transmitters, such as those of the Iridium System. So astronomers are now studying a variety of diverse approaches to mitigating the effects of RFI on their observations [1]. Some of these exploit particular characteristics of specific sources of RFI, such as its location, if from a geostationary satellite, or its polarization. Indeed, since man-made signals are often highly polarized, whereas the inherent nature of many astronomical signals is unpolarized, Deshpande [2] proposes the use of a mitigation technique based on the unpolarized, relatively RFI-free signal. In this paper we compare and contrast this approach with several other post-detection approaches to the identification and mitigation of RFI originating from the Iridium System.

OBSERVATIONS

The Iridium L-band CDTM signal has two helpful features for us, as it is strongly polarized, and, more unusually, has a satellite down-link time-multiplexed in the same band as the phone handset up-link signal. Moreover, as most of Iridium's customers near Puerto Rico are on yachts, local terrain generally screens their up-link signals, which allows the folding of our data at the 180 msec Iridium-dictated period, and the use of intervals with little RFI as a control sample. The Iridium System presently operates within a 1618.85 to 1626.5 MHz band adjacent to the 1610.6-1613.8 MHz Radio Astronomy Service (RAS) band. But it also produces a comb of RFI, with a characteristic 333 kHz spacing, that extends well beyond its licensed band. The ~1 Jy typical intensity of this comb in the RAS band is comparable with that of many of the brighter OH/IR stars that are the astronomical targets. It is noteworthy that no pre-launch simulation available to the ITU or to radio-astronomers gave any hint of the existence of this noxious artifact, which we only see when a satellite passes near our main beam: the ~80 dB forward gain of the Arecibo telescope usually protects us from this particular RFI artifact. Hence it is the in-band transmissions from Iridium that are detected here by our telescope's far side-lobes. The Iridium System is lightly loaded in the Caribbean at present, so there are very few native inter-modulation products in its signal.

Our test data were acquired with full Stokes (I, Q, U, V) parameters as high time-resolution, single-dish spectra. Dynamic 1024 channel spectra were recorded every millisecond using the 9-level sampling mode of an autocorrelator simultaneously in both the Iridium band, using a 25 MHz bandwidth centered at 1621 MHz, and in the RAS band using a 3.125 MHz bandwidth with proportionately finer spectral resolution. The data were checked for inter-modulation products and gain-compression effects induced in the receiving system by the Iridium signal by generating correlation maps [2]. These accumulate the net temporal correlation between fluctuations in every possible combination of spectral channels from every possible pairing of spectra: they are produced as cross-correlations between spectra in the native linears, in I, in the unpolarized flux, I_{UnP}, as well as between the two observed bandwidths, and as autocorrelations of spectra. After folding 2 minutes of data at the period of the Iridium clock cycle, the only Iridium artifacts in our RAS band data are momentary gain compression episodes [3]. The ratio of rms values in this band between cycle phases with(out) RFI is ≈ 1.

The intensity of the Iridium clock synchronization signal generates some ringing in the adjacent spectrum, despite our nine-level sampling, so our data is always hanning smoothed, as, for instance, in Fig. 1. Detailed channel by channel examination of the data, shows that there is still a noticeable under-correction of data in frequency bins immediately before and after the synchronization impulse, and we find that this exaggerates the residuals in comparisons with I_{UnP}: data in Figs 2 & 3 are therefore hanning smoothed twice. The bandpass gain calibration is applied to the linear polarization data before computing Q & I_{UnP} from the Stokes $I, Q, U, \& V$ of each channel of each spectrum as $I_{UnP} = I - \sqrt{Q^2 + U^2 + V^2}$, which reduces the residuals from I_{UnP}.

MITIGATING

All of the examples below use 25 MHz bandwidth data obtained towards the OH/IR star IRAS 17256+0504 on 9th September 2004. Fig. 1 shows a typical, 180 msec sequence of spectra with the OH/IR star at ~1612 MHz and Iridium's signal between 1620-1627 MHz. The mean side-lobe response of the strongest Iridium Stokes I feature here, which is only seen for ~5% of the time, has ~7 times the intensity of our *strong* OH/IR star seen with the main beam. So Iridium can easily saturate an astronomical receiver [3]. Perhaps the simplest mitigation approach is to use the robust mean, which only discriminates against obviously non-gaussian components in a series. It is computed from (and may modify) the temporal sequence of each frequency channel. While the robust mean excises most of the strong RFI in Fig. 1, though leaving a clear residue in the average spectrum circa 1621 & 1625.5 MHz and a broad, slight one circa 1624.5 MHz, the vertical panel shows that it otherwise tracks I. The residues from the robust mean in the average spectrum in effect arise from integrating up features below the robust threshold. On the other hand a similar plot for the second mitigation approach using I_{UnP} shows no evident sign of an Iridium signal. So I_{UnP} over short, one-on-one, time comparisons appears to provide better mitigation, and its output is improved further by applying a robust mean. Yet the efficacy of I_{UnP} relies on the estimation of the *polarized* component, which is both statistically over-estimated and least accurate for weak features: indeed the strongest RFI features are the most accurately excised, as the estimation of the polarized flux is then done with the best S/N, while that of the weakest is subject to a statistical bias, for which no allowance is made here. And I_{UnP} also leaves residuals when RFI is not completely polarized, as Fig. 2 shows at ~1622 MHz, and Fig. 3 for features circa 1624 & 1626 MHz. But folding spectra, as Fig. 2 does, permits both weak RFI feat-

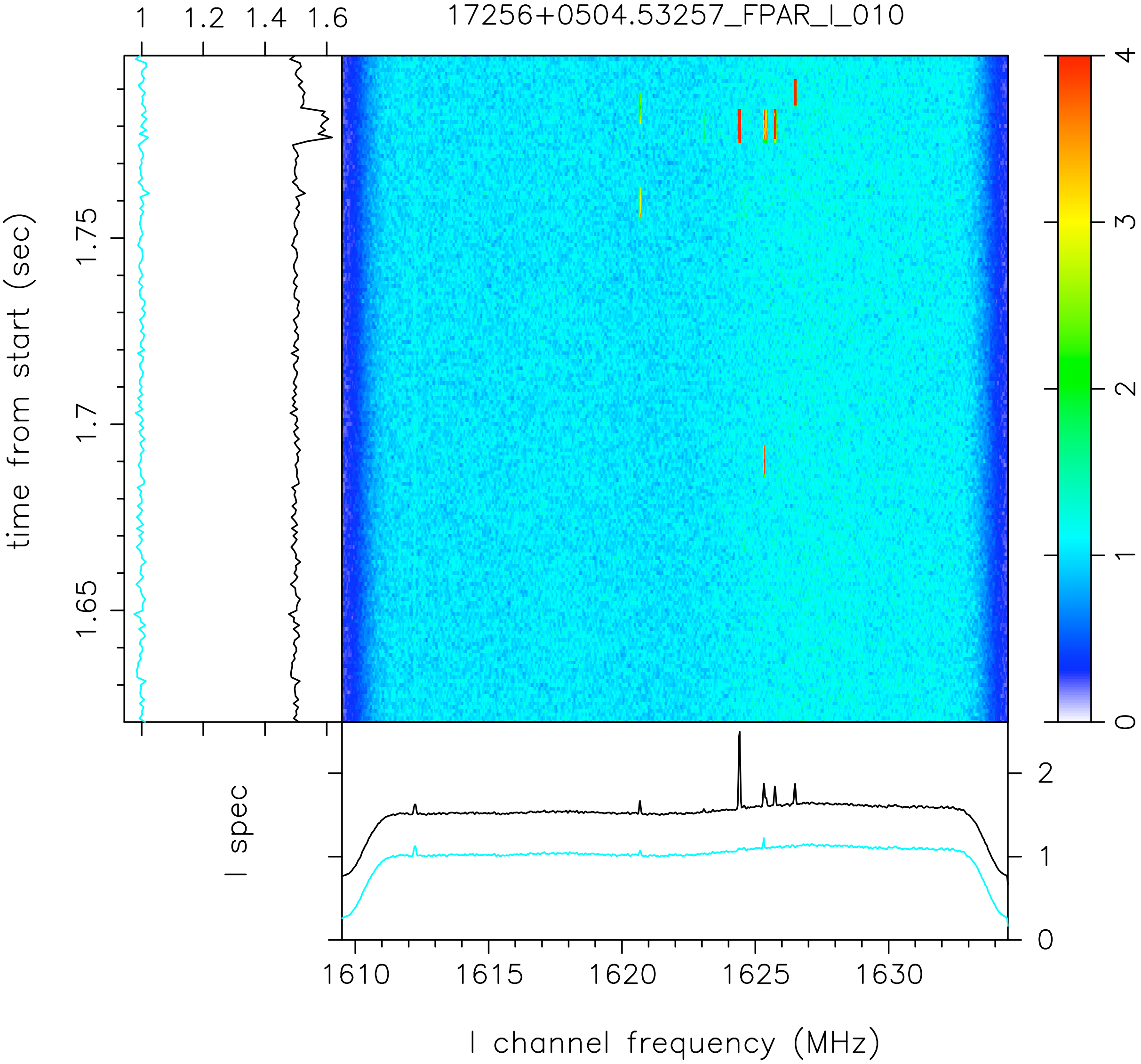

Fig 1: A 180 msec sequence of Stokes I spectra taken at 1 msec intervals, together with their arithmetic (black) and robust (coloured) means on each axis. Only the ~1612 MHz feature comes from the star.

ures below the robust mean's threshold and, as the second panel in Fig. 3 shows, any coherent distortions in the estimation of I_{UnP}, to emerge from the noise. Finally the folded spectra of Fig. 2 offer a third approach to mitigation, as portions of the Iridium cycle without RFI are readily identified from its left-hand panel. We select "RFI-free" spectra by additionally requiring that their integrated total power lies within 3σ of the mean of the set. Figs 2 &3 include RFI-free means.

Fig. 3 enables the integrated-up, coherent deviations to be exhibited. It shows that much the largest deviation occurs in I_{UnP} on the ascending edge of the bandpass at ~1610.5 MHz, near a resonance in the ortho-mode transducer where the polarization properties of the receiver change rapidly. Since its specific properties were not addressed here, we discount it. All of the other excursions in the difference sets occur in the vicinity of evident RFI, with the strongest (circa 1621 MHz) linked to weak RFI in both the robust and unpolarized means, and the largest linked to the robust means. Nevertheless there are no systematic deviations in either approach over most of the spectrum. Table 1 shows the attenuation in dB achieved with the features in Fig. 3. It should be noted that the Iridium data stream is more than usually amenable to treatment by the robust approach on its own, as its occupancy of its band is both episodic and less than 50 %. In cases where strong RFI has a much higher fractional occupancy, so there is little uncontaminated data, the robust mean on its own will fail, whereas that situation is usually greatly improved if I_{UnP} is appropriate and available.

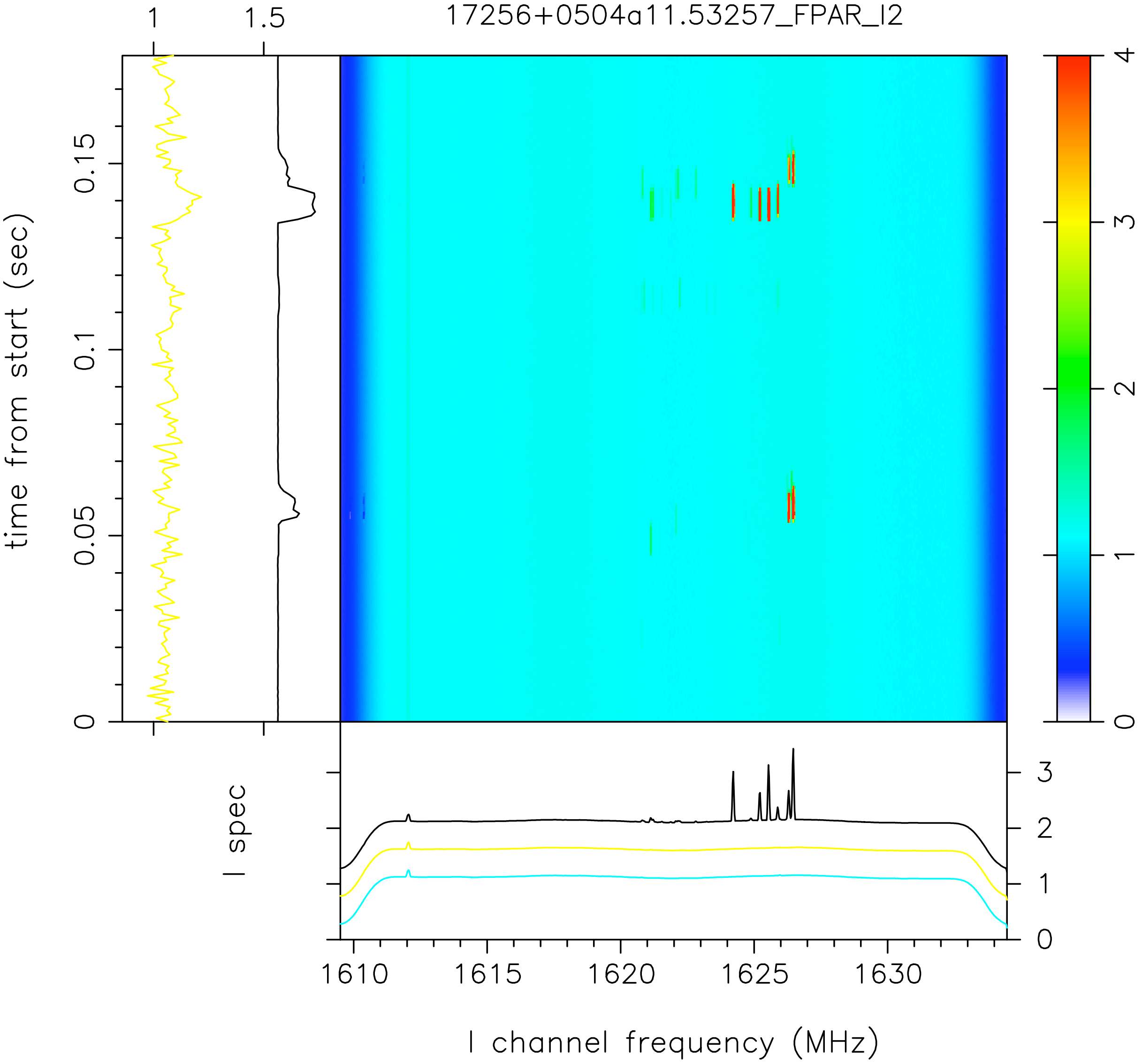

Fig. 2: Stokes I, gain-calibrated data (black) folded for two minutes at the 180 msec Iridium period. These are compared to the robust (yellow) and the "RFI-free" I average from the first 40 msec of the Iridium cycle (sea-green), after limiting its constituents to band means that are within 3 sigma of the overall mean. The band averages for each millisecond of the Iridium cycle are shown on the left, with I offset by 0.5 and the robust mean, z, displayed as (z(t) - <z>)*100 + <z>.

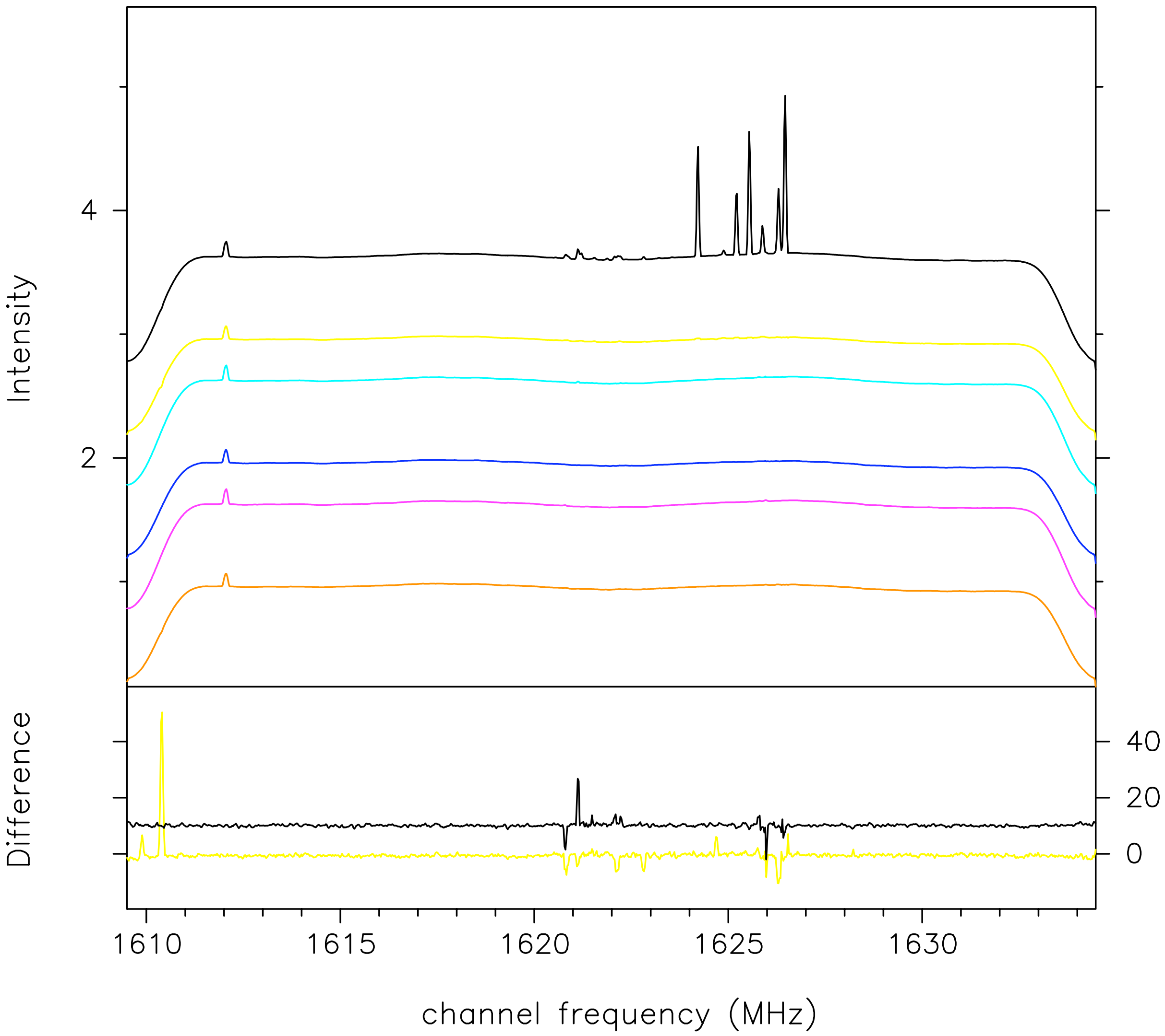

Fig. 3: The two minute folded-mean spectra in descending order in T_{sys} units: (1) arithmetic average Stokes I (black); (2) I_{UnP} (yellow); (3) robust mean of I (sea-green); (4) robust mean of I_{UnP} (blue); (5) "RFI-free" mean (violet); (6) I_{UnP} mean from the RFI-free set (brown). The second panel shows the differences (3) - (5) in black & (4) - (6) in yellow on a magnified scale, in units of expected rms.

Table 1: Attenuation achieved on the 9 Stokes I features in Fig.3 in order of increasing frequency [3]

method (dB)	1	2	3	4	5	6	7	8	9
robust	-32	-33	-29	-29	-34	-15	-43	-19	-09
unpolarized	-32	-22	-14	-21	-18	-08	-20	-08	-13
I_{Unp} + robust	-32	-28	-38	-27	-28	-15	-33	-18	-23

Our analysis has been carried through on a data stream that is corrected for the polarized flux estimate on the time-scale of the shortest integrations, which is usually the worst case. This processing could be adjusted to improve on hanning smoothing, and by using statistical bias corrections. It could also be better adapted to the needs of spectral-line observers, by iterating the analysis on data processed for longer integration times, such as those of the time-sliced Iridium cycle. Likewise the suppression factor is increased by a further 15 dB (the square root of the number of channels) for those observers who only need a single average power level from the exercise. In summary, we find that a comprehensive approach which recognizes the inherent time, frequency and polarization structure of an RFI source allows for its exceedingly effective excision in the post-detection stage when full Stokes data with suitable time and frequency resolutions are available.

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[1] S. W. Ellingson, *Radio Science*, 40, #5, RS5S01, 2005
[2] A. A. Deshpande, *Radio Science*, 40, #5, RS5S12, 2005
[3] A. A. Deshpande & B. M. Lewis, *supplementary plots at* http://www.naic.edu/~blewis/ursi.html