OPTICAL TERMINAL DEFINITION FOR THE FUTURE SERVICE GROWTH (FSG) MODULE OF THE ADVANCED TRACKING AND DATA RELAY SATELLITE (ATDRSS).

Ronald C. Bruno
Stanford Telecommunications
Reston, Virginia

Ford Kalil
NASA Goddard Space Flight Center
Greenbelt, Maryland

Abstract

At the current time, the planned constellation for the ATDRSS does not eliminate the TDRSS Zone of Exclusion. However, the ATDRSS specification includes an option for a future service growth (FSG) module on each satellite that would support expanded and enhanced services. One of the prime candidates for this FSG is a terminal that would support crosslinks between selected relay satellites of a modified ATDRSS constellation. This would allow the placement of a relay satellite at an orbital location that eliminates the ZOE. An optical implementation for the crosslink terminal is examined in this paper and is shown to be particularly attractive because such a terminal can support high data rate crosslinks with very small apertures. The optical crosslink terminal description developed herein has a telescope aperture of 20 cm, and a transmit power attainable from combined GaAlAs laser diodes, and underscores the fact that an optical crosslink terminal is technically feasible and requires a minimum of precious real estate on an already complex relay satellite. This paper summarizes preliminary analyses and definition studies for such an optical terminal conducted over the past year. This includes the identification of alternative constellations incorporating one or more crosslinks and the description of the service routing requirements for the FSG communications terminal. An optical terminal for the FSG is described that provides the functionality and performance required of a crosslink terminal. The mass and power of the optical terminal are estimated and are well within the defined constraints of the FSG. In addition to serving as a crosslink terminal, the defined optical terminal can also be employed for a number of other applications. These include lunar communications support, precision ranging, direct data distribution, and optical single access service.

1.0 Introduction

1.1 Background. At the current time, the planned constellation for the ATDRSS includes a pair of relay satellites at each of two orbital locations, one near 40° W and another near 170° W, such that all satellites are in view of and directly supported via ground terminals located at the White Sands Complex (WSC). Like the present TDRSS, this ATDRSS constellation would entail a Zone of Exclusion (ZOE) for LEO satellites in which communications and navigation services are not available. However, current plans for the ATDRSS also include an option for a future service growth (FSG) module on each satellite that would support expanded and enhanced services. One of the prime candidates for this FSG is a terminal that would support crosslinks between selected relay satellites of a modified ATDRSS constellation with a relay satellite at an orbital location that eliminates the ZOE. An optical crosslink terminal is particularly attractive because it can support high data rate crosslinks with small aperture telescopes, and therefore requires a minimum of precious real estate on a complex relay satellite. This paper summarizes preliminary analyses and definition studies for such an optical terminal conducted over the past year by the Engineering Directorate at the GSFC. This includes the identification of alternative constellations incorporating one or more crosslinks, description of the required service routing & switching, and definition of an optical communications payload that meets the required functional and performance requirements of an FSG crosslink terminal. Other applications for an FSG optical terminal are explored including lunar communications support, precision ranging, direct data distribution, and optical single access service.

1.2 FSG Description. The ATDRSS FSG refers to a specified amount of mass, size and power that has been allocated for payload growth in order to

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accommodate expansion or enhancement in the services offered by ATDRSS. The current specification values for the FSG [1] are as listed in Table 1. The specification also identifies the requirement for a number of FSG interfaces including command & telemetry, IF & RF signal interfaces, electrical power, thermal and structural.

Mass	240 lbs.
Size	11 ft^3
Power	260 W
Minimum Field of View	±77.5° East-West ±31.0° North-South

Table 1. Key FSG Specifications

2.0 Applications for an FSG Optical Communications Terminal

2.1 Alternative Architectures for ATDRSS ZOE Closure. A variety of options are possible for closing the ZOE with crosslinks between ATDRSS relays. Figure 1 illustrates the baseline ATDRSS constellation along with five alternatives that close the ZOE with one or more crosslinks. All but one of the options require changing the orbital position of only a single relay satellite and involve only a single crosslink between two relays. In these options, one relay is moved from its nominal orbital position to a new one (out of view of the WSC) that closes the ZOE. This out-of-view (OOV) satellite is then supported via a crosslink from one of the in-view relays (IVRs). The supporting IVR is either the spare satellite or an operational satellite. Table 2 summarizes some of the characteristics of the five options examined for ZOE closure that are critical design drivers for the FSG crosslink terminal. Chief among these is the amount of GEO arc that the crosslink spans, which is a key driver for terminal aperture and power. The use of the spare for the IVR that supports the OOV satellite is also an important element because it limits the traffic burden of the IVR SGL. As indicated in Table 2, for Options 3 & 4, the spare serves as the IVR; in these options, the SGL of the IVR therefore supports only the user services provided via the OOV. For the other Options (1, 2, & 5), the SGL of the IVR that supports the OOV potentially must carry twice as much traffic since it contains its directly-supported user services in addition to the services supported by the OOV.

CLOSURE OPTION	XL GEO ARC	# OF XLINKS	ROLE OF SPARE
1	32°	1	baseline
2	16°	2	baseline
3	70°	1	IVR
4	162°	1	IVR
5	32°	1	no spare

Table 2. Range of Crosslink Options

2.2 Lunar, Direct Data Distribution, Single Access, Precision Ranging: Figure 2 illustrates additional applications for an optical FSG communications terminal. This is an important issue because in all but one of the options for ZOE closure, only two crosslink terminals are used, leaving the two or three unused terminals free to serve other purposes. The other purposes identified in Figure 2 are as follows:

- Trunk link to a lunar front-side base
- Optical single access service
- Optical SGL for direct data distribution to first level destinations on the ground
- Precision two-way optical ranging

While none of these applications will be discussed further in this paper, it is important to note that an optical communications terminal identical to that designed for the crosslink can serve a useful and vital function for all of these applications. Accordingly, the optical terminal is not simply a specialized payload supporting a specific function, but rather a general purpose payload, applicable to a number of system & service enhancements and upgrades.

3.0 FSG Switching Requirements.

3.1 Channel Routing Requirements. The most general configuration of two ATDRSS satellites with a crosslink is illustrated in Figure 3. This shows the OOV satellite supporting space users while it is connected to the WSC via a crosslink with an IVR that is an operational satellite. The SGL of IVR satellite, simultaneously supports the OOV-provided services as well as its own complement of space users. Since the FSG is considered to be an identical payload on all relays, it is clear that the FSG must be capable of flexibly routing the SGL, crosslink and user service signals, depending upon the particular role its host satellite plays in the ATDRSS constellation. In all, there are four routing configurations that the FSG must support. These are:

- IVR satellite w/ no crosslink: connects the SGL with user services
- OOV satellite: connects crosslink with user services
- IVR spare relay supporting OOV: connects SGL with crosslink
- IVR relay supporting OOV: connects SGL with both the crosslink and user services

The signal routing requirements of these four configurations that the FSG switch must support are pictorially summarized in Figure 4.

3.2 SGL Channelization Impact. The channel structure and frequency plan of the ATDRSS SGL strongly influences the ways in which the channel routing requirements (identified in 3.1) may be implemented. The SGL channels of the IVR satellite may be used in a number of ways to support the user services provided by the IVR and OOV satellites. The SGL channels may be allocated in the following ways:

- Dedicated to IVR-provided user services,
- Shared by IVR-provided and OOV-provided services, or
- Dedicated to OOV-provided services.

The optimum implementation requires a trade between complexity and efficiency of resource utilization: dedicated SGL channels are simpler to implement, but they use the channel resources (e.g. spectrum and HPAs) less efficiently. It is reasonable to assume a mix of dedicated and shared resources, and Figure 5 illustrates such an implementation for the SGL. In the return link, there are three wide band channels at both Ku-band and Ka-band. Each channel is assumed to be supported by a dedicated HPA. On the Ku-band SGL return link, one HPA is dedicated to a frequency multiplex of all return S-band services and TT&C of the IVR. The other two HPAs each support one wideband single access (SA) user service (KuSA or KaSA) and are shared by both IVR- and OOV-provided services. Similarly, on the Ka-band SGL return, one of the three HPAs supports a mux of all S-band services provided by the OOV, and the other two support wideband KuSA and KaSA services of the IVR and OOV. The forward link SGL structure is similar, with four shared channels for K-band SA services, one dedicated channel for S-band IVR services, and one dedicated to S-band OOV services. All of these are assumed to be at Ku-band.

3.3 Switching Implementation. There are many possible switching implementations that can provide the required routing for the assumed SGL channelization of Figure 5. Based on reliability considerations, an implementation that relies on passive components, such as power dividers and combiners, is preferred. Figure 6 illustrates a suitable switch implementation for the two SGL channels dedicated to S-band user services. One channel is dedicated to IVR-provided user services, and the other is dedicated to OOV-provided services. Figure 7 illustrates an analogous switching implementation for a shared SGL channel. In both figures, the signal paths are labeled with the satellite role or state that requires that routing path to be enabled.

4.0 Crosslink Channelization Implementation

4.1 Waveform vs Digital Channels The critical decisions in the implementation of the optical crosslink are whether the modulation format is digital or waveform, and whether the detection scheme is heterodyne or direct. Although certain heterodyne implementations may be feasible, only direct detection implementations are considered here. With a waveform channel, the transmitting terminal modulates the intensity of a laser with an incoming RF signal mixed down to some suitable IF consistent with laser transmitter and receiver detector bandwidths. At the receiving terminal, an avalanche photo-diode (APD) converts the optical signal back into an electrical signal at IF. A waveform crosslink implementation is thus a non-regenerative bent-pipe repeater, and it is much like a conventional frequency conversion repeater with a transmission frequency equal to the IF frequency that modulates the intensity of the laser transmitter. A digital crosslink implementation, on the other hand, is a regenerative repeater and requires the transmitter to demodulate the incoming RF signal to baseband, and the receiver to remodulate the received digital optical signal back to RF.

The decision of waveform vs digital channel implementation involves a trade between flexibility and efficiency. A waveform implementation offers greater flexibility in that it is transparent to the specific modulation format of the RF carrier but it requires significantly greater optical transmit power than a digital link. For the same signal-to-noise requirement, the ratio of the required peak optical power with a waveform vs a quaternary pulse position modulation (QPPM) digital channel is approximately given by the following expression:

$$\frac{P_W}{P_D} = \frac{1}{m^2/4}\left[\frac{1+\sqrt{1+\frac{m^2}{4}\frac{FOM}{B\cdot SNR}}}{1+\sqrt{1+\frac{FOM}{B\cdot SNR}}}\right]$$

where m is the modulation index of the waveform modulated signal, B is the signal bandwidth, and FOM is a receiver figure of merit dependent on receiver sensitivity. [2] Typically, FOM is quite large (on the order of 10^{10}), so for very high bandwidth channels where the contribution from the FOM term is small, the ratio is dominated by the inverse $\frac{1}{4}m^2$ term. For a single carrier, m can be no larger than 0.9, so it is seen that a digital channel requires at least 6 dB less peak power than a waveform channel. In addition, since the waveform channel is not regenerative, another roughly 6 dB must be paid in achieving a greater SNR in order to avoid severe degradations from the cascade of non-regenerative links. Thus, it is clear that at high data rates, a waveform channel suffers a 10-12 dB power penalty relative to a QPPM digital channel. For lower data rates, where the FOM term dominates, the waveform penalty is a few dB less. However, for a channel composed of multiple carriers at low data rates, such as the channels supporting S-band services referred to above, the waveform penalty will be much greater than single carrier channels. Because the sum of the m values for all the individual carriers cannot be much greater than 1, and since the signal power goes as m^2, many small channels are supported less efficiently than a single channel with a data rate equal to the sum of the small channel data rates.

4.2 Implementation Description. Given that waveform and digital channels each have particular advantages and disadvantages, it is reasonable to expect that the optimum crosslink implementation would employ a combination of both waveform and digital channels. A waveform channel is appropriate where the flexibility of bent-pipe transfer is needed and the supported data rates are not too high. Such is the case with the multiplexed channel of S-band services described above. Accordingly, we have assumed such an implementation for the channel that supports S-band services that are relayed over the crosslink. Conversely, for the high bandwidth K-band SA services where users tend to operate at a limited number of high data rates, less flexibility is needed and the transmitter power requirements for a high data rate favors a more efficient modulation format. For these reasons, the implementation we have assumed for the channels supporting K-band SA services is a digital one that requires demodulation and remodulation at the optical transceiver terminals.

The crosslink implementation we have assumed, thus has a waveform channel for S-band services and two digital channels for K-band services in both forward and return directions. With this design, the OOV satellite would be capable of simultaneously supporting the full complement of S-band services and any two of the four possible KuSA and KaSA services. Figures 8 and 9 illustrate the bent-pipe processing by the IVR satellite of the forward and return link waveform channels, respectively. In both directions, it is assumed that a 100 MHz bandwidth is sufficient to incorporate the frequency multiplex of all S-band services (plus the pilot tone and TT&C, as applicable) that are supported by the waveform channel. It is also important to note that the crosslink waveform channel is just a frequency shifted version of the same channel at K-band on the SGL. Thus in order to implement the required routing, the FSG need only to select the appropriate 100 MHz of SGL bandwidth and convert it in frequency to match the assumed 300 MHz IF of the optical crosslink waveform channel.

5.0 Communications and Tracking Performance Analysis

5.1 Power Requirements at the Receiver. The communications performance over the crosslink is determined by the chosen modulation format, the supported services, the receiver sensitivity, and the amount of optical power arriving at the receiver. The crosslink implementation described in 4.2 consists of both waveform and digital links. The digital links are sized to support up to 650 Mbps which is the maximum specified for KaSA services. With a QPPM modulation format, the average power required to support a 650 Mbps crosslink with a 10^{-6} BER is roughly -80 dBW, which corresponds to about 65 photons per bit. The required peak power would be four times as large, or -74 dBW. The power requirements for the waveform links are calculated assuming that a 20 dB *SNR* is maintained for all the services supported by the crosslink. The average optical power required at the receiver in order to achieve a desired *SNR* over a bandwidth *B* associated with a single carrier is given by: [2]

$$\frac{eF\left[1+\sqrt{1+\left(\frac{m^2}{2B\cdot SNR}-RIN\right)\frac{FOM}{2}}\right]}{\rho\left(\frac{m^2}{2B\cdot SNR}-RIN\right)}$$

where *m* is the modulation index of the carrier, *e* is the electron charge, *F* is the APD excess noise figure, ρ is the APD responsivity, *m* is the modulation index of a carrier, *RIN* is the relative intensity noise of the optical transmitter and *FOM* characterizes the APD and its associated preamp. Assumed values for the receiver transmitter performance parameters are as follows:

- APD responsivity (ρ): 0.62 A/W
- Excess Noise Figure (*F*): 4.1 dB
- RCVR Figure of Merit (*FOM*): 1.5 10^{11}, with 1 nA APD dark current, 2 pF capacitance, and 300° pre-amp
- Rel. Intensity Noise (*RIN*): 10^{-14} per Hz

It is clear that the value of *m* determines how much of the total average power is translated into signal power associated with a given carrier; a smaller *m* value requires a larger average power. The return crosslink channel supports 9 subcarriers: 2 S-band single access (SSA) services at up to 6 Mbps, 5 S-band multi-access (SMA) services at up to 3 Mbps, one Beacon service, and one TT&C link. For simplicity, on the return link crosslink waveform channel, we have assumed the same *m* of 0.14 for each of the nine carriers. Since all carriers are assigned the same *m*, the required power at the receiver will be driven by the most demanding signal, which in this case is the 6 Mbps SSA. With the above assumptions concerning receiver sensitivity and modulation index, the required average power at the receiver required to support the return waveform crosslink is roughly -71 dBW. The forward crosslink supports 7 carriers consisting of 2 SSAs, 2 SMAs, one Beacon, one TT&C, and a pilot tone to drive the master frequency generator of the OOV satellite. The most demanding service carrier is again the SSA, but at a maximum of 300 Kbps, the total average received power to support the forward crosslink is -84.5 dBW if we again assume an *m* of 0.14 for each carrier.

5.2 Link Budget Analysis. In Table 3, the link budget over 32° of GEO arc, 20 cm telescopes and a 300 mW optical transmitter of combined GaAlAs laser diodes (850 nm) is illustrated.

LINK ITEM	VALUE dB(W)
Average Transmit Power	-5.2
Transmitter Gain	117.4
Transmitter Losses	-6.3
Range Loss	-290.7
Receiver Gain	117.4
Receiver Losses	-2.4
Power at Receiver Detector	-69.8
Return WF Required Power	-84.5
Return Link Margin	1.2
Forward WF Required Power	-71.0
Forward WF Link Margin	14.7
Return Digital Req Power	-74.0
Return Digital Link Margin	4.2

Table 3: Optical Crosslink Link Budget

Table 3 shows that, with respect to average power, the digital return channels enjoy a 3 dB better margin than the waveform channels. However, the peak power requirements are roughly the same because for digital QPPM the peak-average power ratio is 4, while for waveform modulation it is only about 2. Thus a 600 mW peak power source could support either a digital or a waveform return channel with just over a 1 dB margin.

6.0 Description of Optical Communications Terminal Payload

The primary motivation for conducting this work was to derive the high-level functional and performance requirements of the FSG crosslink terminal and to determine whether an optical implementation could fulfill those requirements within the size, weight, and power constraints imposed upon the FSG. The functional and performance issues have been discussed in previous sections. Here we deal with the estimation of optical terminal weight and power. Our approach to this has been to develop the terminal block diagram down to a level that the mass and power of the components identified can be estimated based on data for existing and planned payloads.

Figure 10 contains an overview of the optical FSG payload and its relationship to the rest of the spacecraft. The switch assembly includes one switch of the type identified in Figure 6 and three of the type in Figure 7. The optical transceiver identified in Figure 10 is shown in greater detail in Figure 11. This clearly shows 3 forward and return channels which are combined via λ-division multiplexing. All the channels share a common telescope, optics, pointing assembly & control, and signal acquisition & tracking subsystem.

The weight and power counted against the optical FSG terminal is grouped into 3 categories in Table 4. These are, the bare terminal, the switch assembly, and the required augmentation of the SGL to relay the OOV-services.

ITEM	MASS (lbs)	POWER (W)
OPTICAL TRANSCEIVER	150-190	90-125
QPSK MODEMS (2)	22	20
MIXERS/MUX/DEMUX	6	15
SGL HPA + MIXER	7	16
SGL LNA + MIXER	5	8
SWITCH ASSEMBLY	12	3
TOTAL	202-242	152-187

Table 4: Mass & Power Estimates of the Optical FSG Terminal

7.0 Summary Conclusions

An optical communications terminal for the ATDRSS FSG appears to be both feasible and attractive. Currently available technology can support the terminal's requirements, and preliminary mass and power estimates are within the constraints specified for the FSG. An optical terminal could enable ZOE closure by supporting a crosslink in the ATDRSS constellation. However, a terminal designed for the crosslink application could also support a number of other applications including lunar communications support and precision ranging. Accordingly, the optical terminal is not simply a specialized payload for a specific function, but rather a general purpose payload, applicable to a number of potentially vital and useful future service enhancements and upgrades.

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References

1. *Phase B ATDRSS System Requirements Specification*, November 1989, S-500, NASA GSFC Document

2. R.G. Marshalek and G.A. Koepf, August 1988, *Comparison of Optical Technologies for Intersatellite Links In A Global Telecommunications Network*, Optical Engineering, Volume 27, Number 8

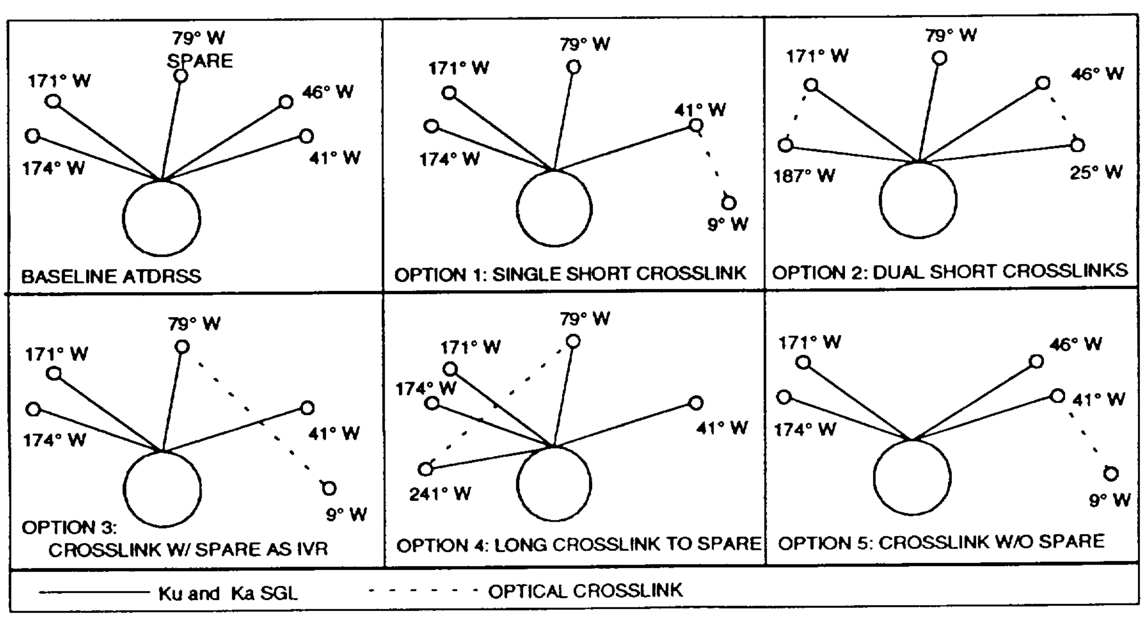

Figure 1: Example ATDRSS ZOE Closure Options

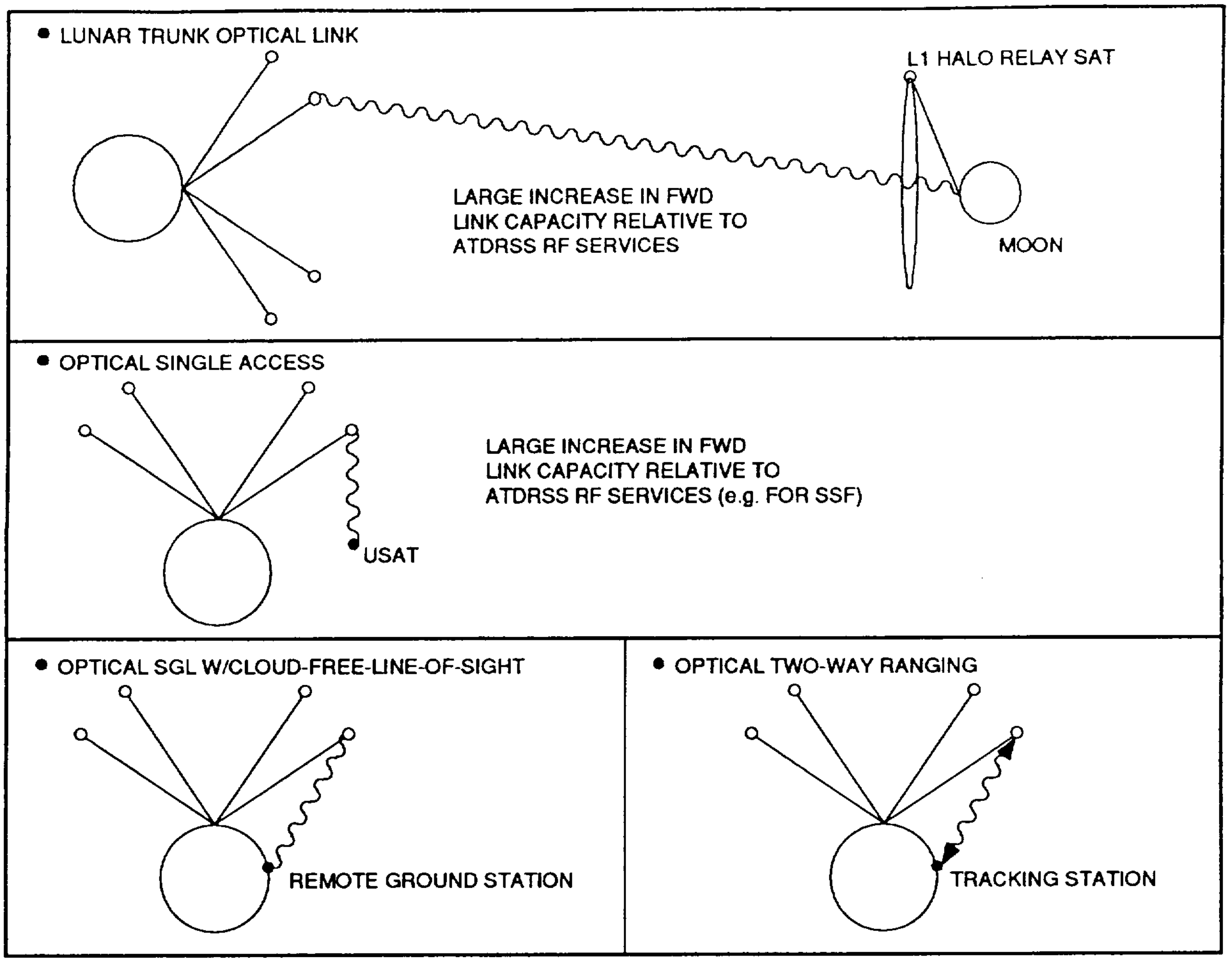

Figure 2: Other Potential Applications for an Optical Terminal

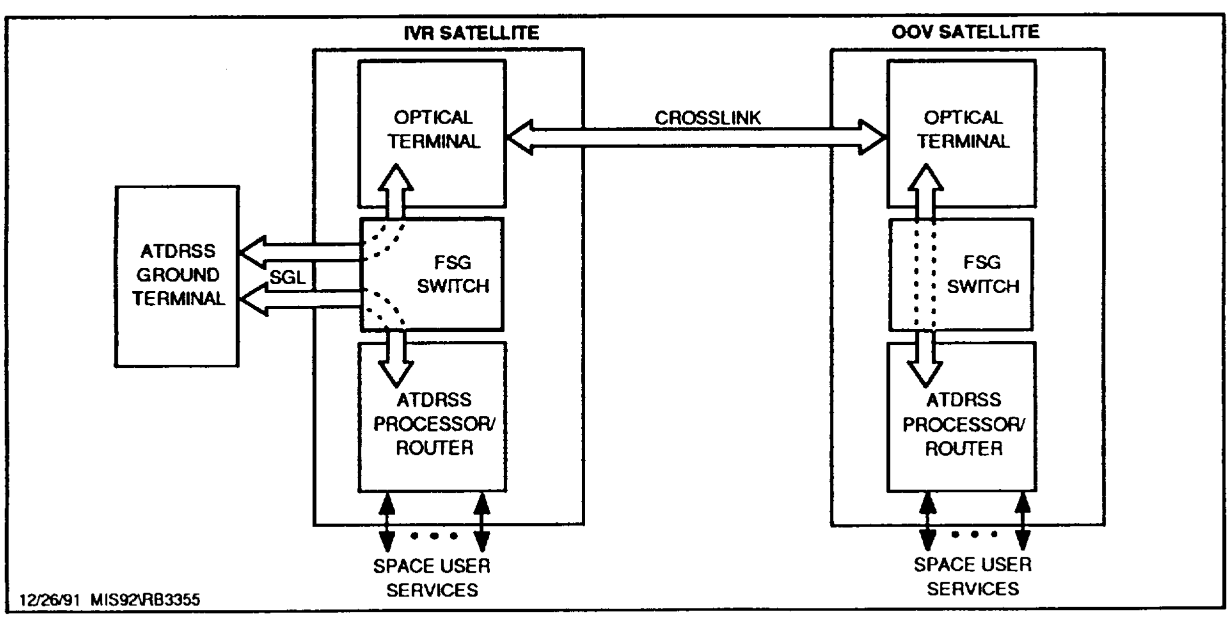

Figure 3: Routing Requirements of the FSG Switch

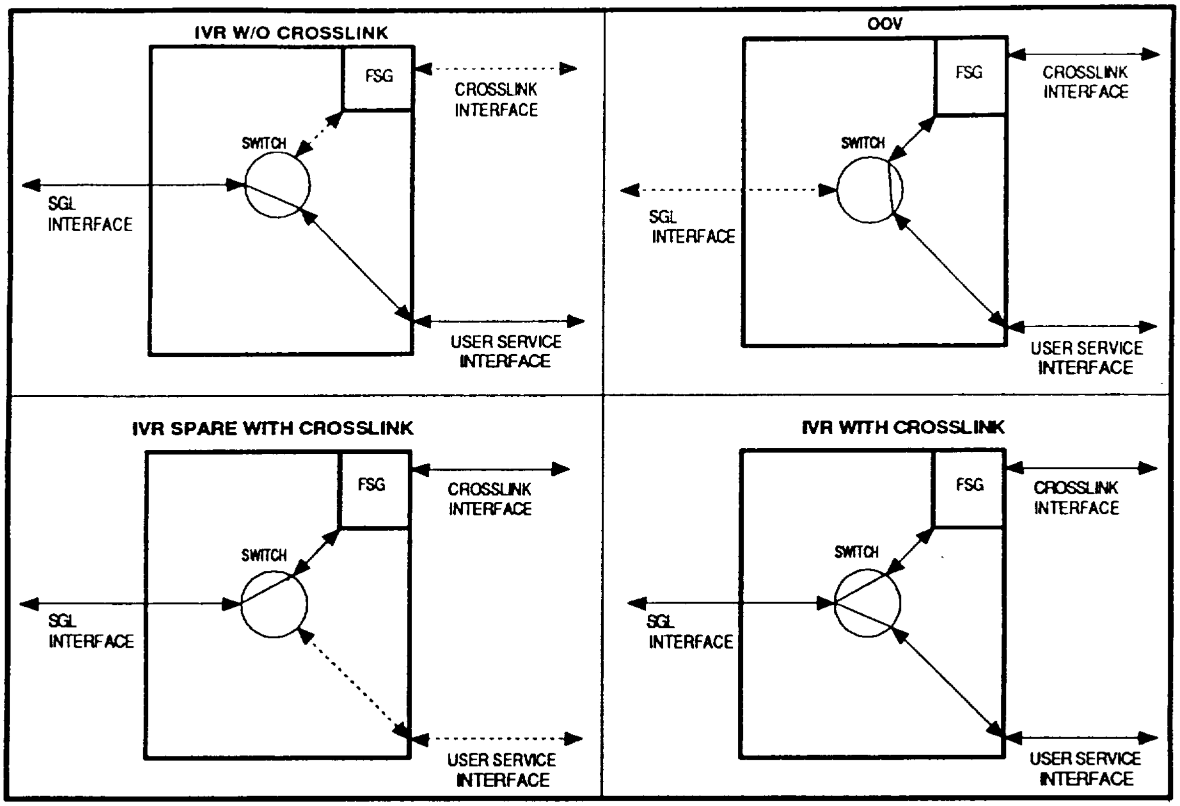

Figure 4: FSG Channel Routing Requirements in All Configurations

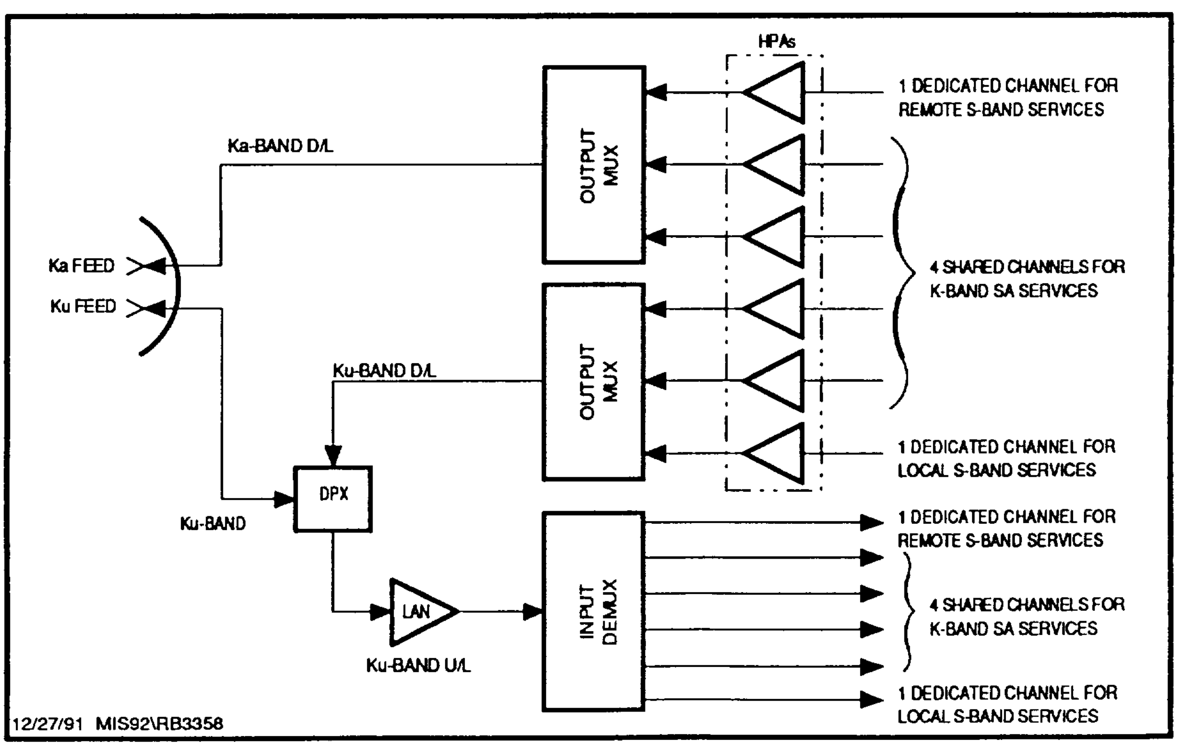

Figure 5: Example ATDRSS SGL Channelization Implementation

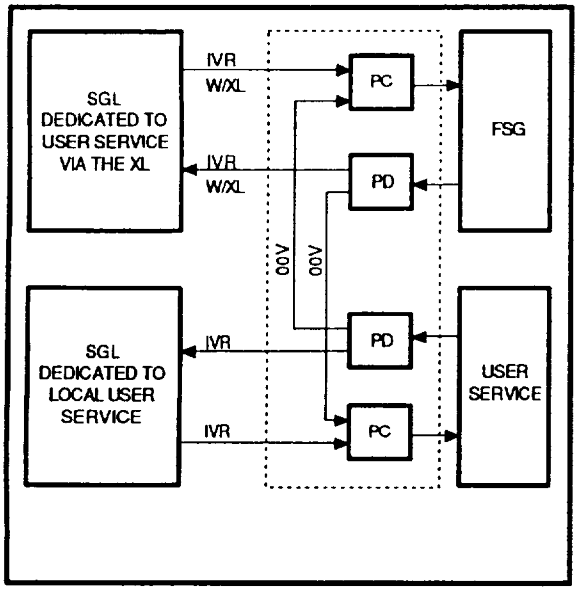

Figure 6: Example Switch Implementation with Dedicated SGL Channels for S-Band Services

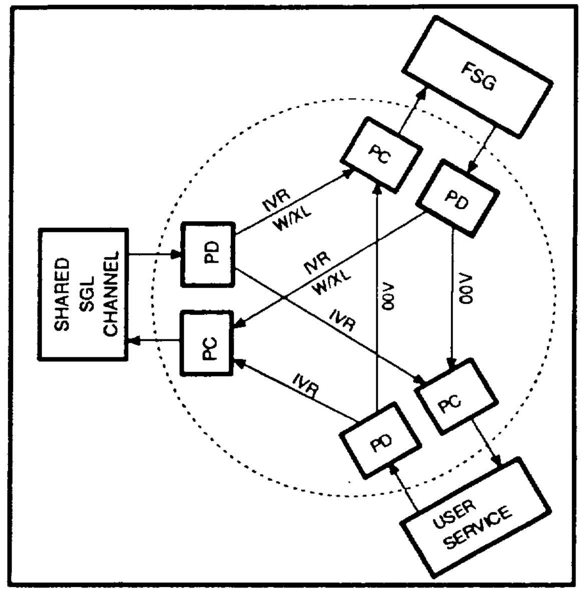

Figure 7: Example Switch Implementation with Shared SGL Channels

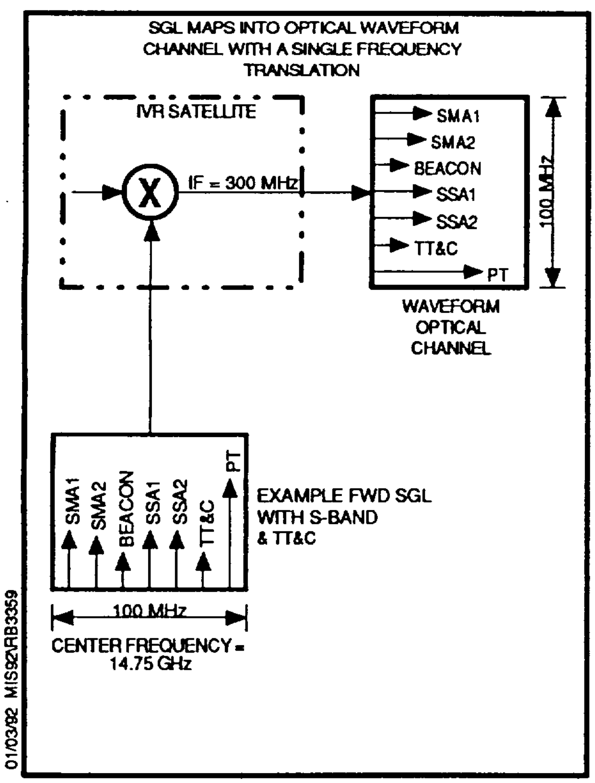

Figure 8: Waveform Forward Crosslink

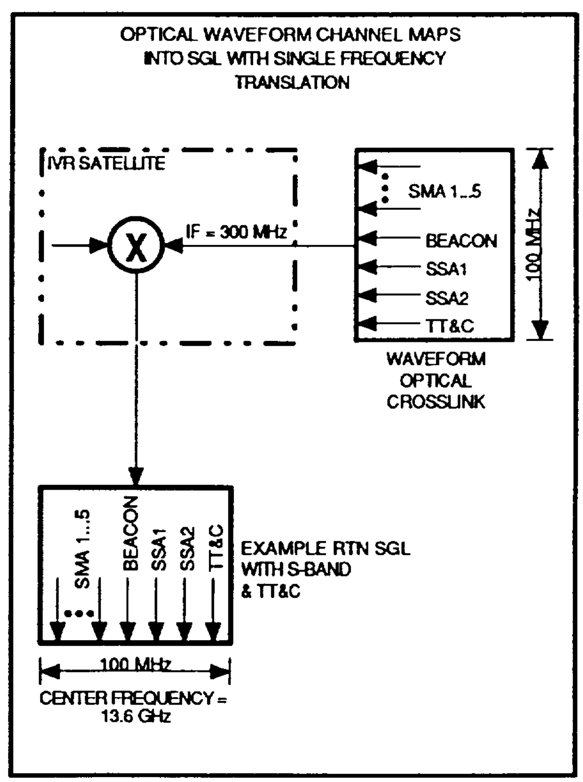

Figure 9: Waveform Return Crosslink

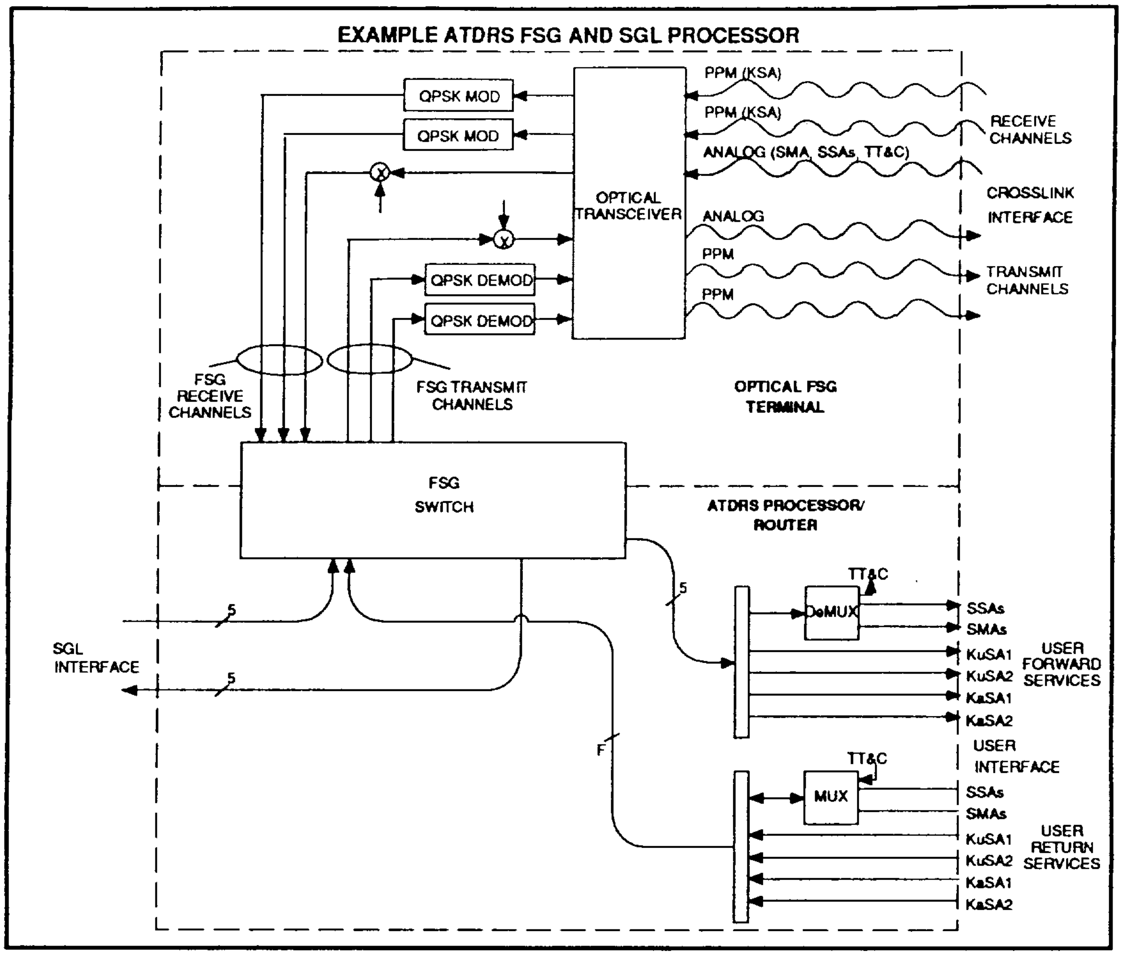

Figure 10: Overview of the FSG Payload

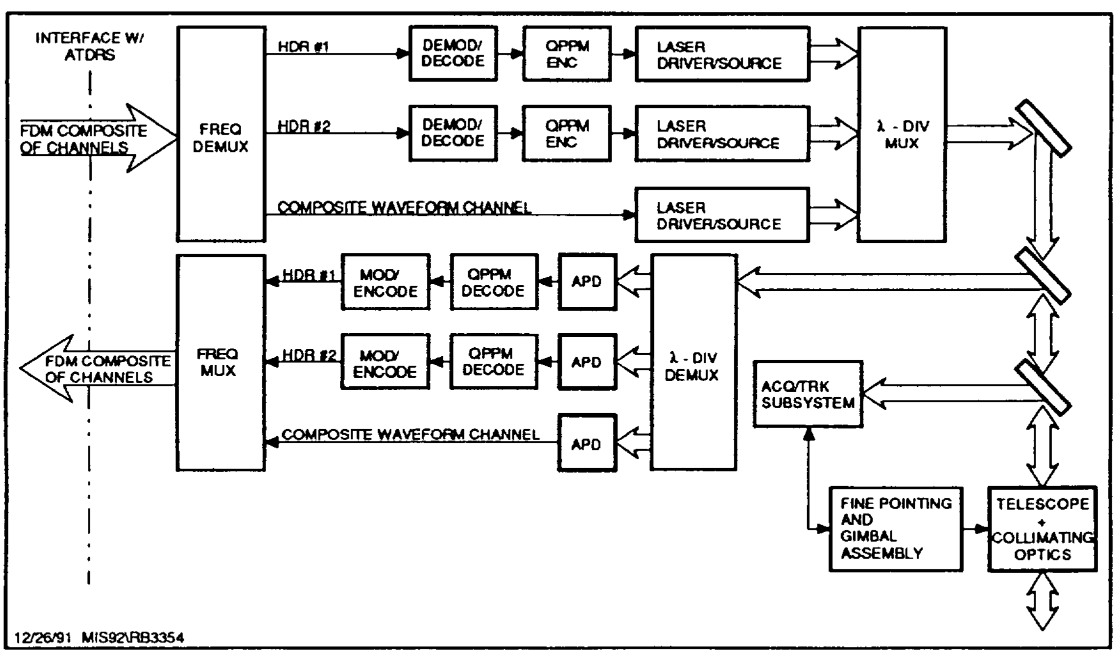

Figure 11: Optical Transceiver Payload for FSG