Chapter 5
GCE-BOC Modulation: A Generalized Multiplexing Technology for Modern GNSS Dual-Frequency Signals

Xinming Huang, Xiangwei Zhu, Xiaomei Tang, Hang Gong and Gang Ou

Abstract For the purpose of structural enhancement and backwards compatibility, more than two binary signals on one carrier frequency are required to emit. In order to maximize the power efficiency, constant-envelope modulation is adopted. Alt-BOC and ACE-BOC modulations, the constant-envelope modulation that multiplexes four binary spreading codes as two QPSK signals at two different carrier frequencies, are proposed by Galileo and BeiDou respectively. A constraint of these new modulations is that the number of signals to be multiplexed must be no larger than four signal channels. In this paper, a generalized dual-frequency constant-envelope multiplexing technology, named generalized constant envelope BOC (GCE-BOC) modulation, is presented. The modulation can be regarded as the extended form of Alt-BOC and ACE-BOC modulations and provides a solution to dual-frequency constant envelope multiplexing problem for worldwide GNSS.

Keywords GNSS · Dual-Frequency · Constant envelope · GCE-BOC

5.1 Introduction

For the purpose of structural enhancement and backwards compatibility, more than two binary signals on one carrier frequency are required to emit [1]. In order to maximize the power efficiency, constant envelope modulation is adopted. Several multiplexing techniques, including Interplex, CASM, majority signal voting and phase-optimized constant envelope transmit (POCET) technology, are proposed in

X. Huang · X. Zhu · X. Tang · H. Gong · G. Ou (✉)
Satellite Navigation R&D Center, National University of Defense Technology, Changsha 410073, China
e-mail: ougang_nnc@163.com

J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2015 Proceedings: Volume II*, Lecture Notes in Electrical Engineering 341,
DOI 10.1007/978-3-662-46635-3_5

order to solve the problem of constant envelope transmitting several signals in a center frequency [2–4]. While for some applications, signals on dual-frequency are required to transmit with constant envelope. The typical dual-frequency constant envelope modulation technologies include Alt-BOC modulation, which is the constant-envelope modulation adopted by Galileo to multiplex four codes with equal power on E5 band [5], and ACE-BOC modulation, which is the optional constant-envelope modulation preferred by BeiDou system to multiplex four codes with unequal power on B2 band [6]. Both Alt-BOC and ACE-BOC modulations can solve the problem of constant envelope transmitting dual-frequency signals. A constraint of Alt-BOC and ACE-BOC is that the number of signals to be multiplexed must be no larger than four signal channels, which is not always the very constraint for some transmission applications. A more generalized problem is to multiplex arbitrary number of signals on two sidebands into a signal with constant envelope.

Dual-frequency constant envelope modulation technology has wide applications prospects. For example, for backward compatibility of BeiDou B1 signals, a regional signal and two global signals with 14.322 MHz center frequency difference must be multiplexed, which is a typical dual-frequency multiplexing problem. A proposed application to GPS III is to combine the L2C, L2-P(Y), and L5 signals into a constant-envelope signal transmitted by a single power amplifier, which is also a typical dual-frequency multiplexing problem [7]. Moreover, GLONASS system has an attempt to constant envelope transmit the traditional FDMA signal with a CDMA signal in dual frequencies [7, 8].

In order to solve the problem of multiplexing arbitrary number of signals on two sidebands into a signal with constant envelope, we present a generalized dual-frequency constant envelope modulation named GCE-BOC modulation. Then its application on BeiDou B1 band is discussed. The paper is organized as follows: In Sect. 5.2, the principle of GCE-BOC modulation is introduced. Secondly, the applications of GCE-BOC modulation on Beidou B1 band are presented and analyzed in Sect. 5.3. Finally conclusions are drawn in Sect. 5.4.

5.2 GCE-BOC Modulation

Assume the generalized dual-frequency multiplexing problem as combining several signals on two sidebands into an integrated signal in which $s_k(t)\, k = 1, 2, 3\ldots N$ are located on the lower sideband, $\tilde{s}_j(t)\, j = 1, 2, 3\ldots M$ are located on the upper sideband. On each sideband the signals are modulated into a constant envelope signal, with the center frequencies of two sidebands $2f_{sc}$ apart. Any multiplexing technology can be chosen, including Interplex, CASM, majority signal voting and phase-optimized constant envelope transmit (POCET) technology. The signals on the lower sideband modulated as a constant envelope signal by the chosen multiplexing technology can be expressed as

$$\begin{cases} s_{up}(t) = s_{up}^{r}(t) + js_{up}^{i}(t) \\ s_{down}(t) = s_{down}^{r}(t) + js_{down}^{i}(t) \end{cases} \tag{5.1}$$

where $s_{up}^{r}(t)$ and $s_{up}^{i}(t)$ are real and imaginary parts of the constant envelope signal located on the upper sideband, $s_{down}^{r}(t)$ and $s_{down}^{i}(t)$ are real and imaginary parts of the constant envelope signal located on the lower sideband.

The dual-frequency baseband signal modulated as a constant envelope signal by the Interplex modulation can be expressed as

$$\begin{aligned} s_{\Sigma}(t) &= (s_I(t) + js_Q(t))e^{-j2\pi f_{sc}t} + (\tilde{s}_I(t) + j\tilde{s}_Q(t))e^{j2\pi f_{sc}t} \\ &= \alpha_1 \sin(2\pi f_{sc}t + \varphi_1) + j\alpha_2 \sin(2\pi f_{sc}t + \varphi_2) \end{aligned} \tag{5.2}$$

where

$$\begin{aligned} &\begin{cases} \alpha_1 = \sqrt{(s_I(t) + \tilde{s}_I(t))^2 + (s_Q(t) - \tilde{s}_Q(t))^2} \\ \alpha_2 = -\sqrt{(s_Q(t) + \tilde{s}_Q(t))^2 + (s_I(t) - \tilde{s}_I(t))^2} \end{cases} \\ &\begin{cases} \varphi_1 = \operatorname{atan2}[s_I(t) + \tilde{s}_I(t), s_Q(t) - \tilde{s}_Q(t)] \\ \varphi_2 = -\operatorname{atan2}[s_Q(t) + \tilde{s}_Q(t), s_I(t) - \tilde{s}_I(t)] \end{cases} \end{aligned} \tag{5.3}$$

And atan 2(•,•) is four-quadrant arctangent.

By employing a 2-level waveform like the BOC subcarrier as the subcarrier [8], we can get the constant envelope modulation baseband signal as GCE-BOC modulated signal, which can be expressed as

$$s(t) = \alpha_1 \operatorname{sgn}[\sin(2\pi f_{sc}t + \varphi_1)] + j\alpha_2 \operatorname{sgn}[\sin(2\pi f_{sc}t + \varphi_2)] \tag{5.4}$$

GCE-BOC modulation is expressed as the form of GCE-BOC$_{(m,n)}$ in the paper, where m denotes the number of signals in the lower sideband, and n denotes the number of signals in the upper sideband.

Considering multiplexing four signals into an integrated signal in which $s_1(t)$ and $s_2(t)$ are located on the lower sideband, $s_3(t)$ and $s_4(t)$ are located on the upper sideband, with the center frequencies of two sidebands $2f_{sc}$ apart. QPSK is the most widely used modulation for traditional navigation signals. The quadrature phase relationship provides good cross-correlation protection between the two spreading codes. Thus we adopt QPSK as the constant envelope modulation method for each sideband. Consequently, the dual-frequency constant envelope modulation baseband signal can be expressed as

$$s(t) = \alpha_1 \operatorname{sgn}[\sin(2\pi f_{sc}t + \varphi_1)] + j\alpha_2 \operatorname{sgn}[\sin(2\pi f_{sc}t + \varphi_2)] \tag{5.5}$$

where

$$\begin{cases} \alpha_1 = \sqrt{(s_1(t) + s_3(t))^2 + (s_2(t) - s_4(t))^2} \\ \alpha_2 = -\sqrt{(s_1(t) - s_3(t))^2 + (s_2(t) + s_4(t))^2} \end{cases}$$
$$\begin{cases} \varphi_1 = \arctan[(s_1(t) + s_3(t)), (s_2(t) - s_4(t))] \\ \varphi_2 = -\arctan[(s_2(t) + s_4(t)), (s_1(t) - s_3(t))] \end{cases} \quad (5.6)$$

As can be seen, the special case of GCE-BOC modulation for four signals has the same analytical expression as ACE-BOC modulation, thus the GCE-BOC modulation can be regarded as the extended form of ACE-BOC modulation.

By combing the constant envelope signals on the both sidebands, the multiplexing efficiency can be expressed as

$$\eta = \left(\frac{\sum_{k=1}^{N} P_{s_k} + \sum_{j=1}^{M} P_{\tilde{s}_j}}{\alpha_1^2 + \alpha_2^2} \right) \quad (5.7)$$

where P_{s_k} is the power of $s_k(t)$, $P_{\tilde{s}_j}$ is the power of $\tilde{s}_j(t)$.

As the fraction of fundamental harmonic in square wave is 81.06 %, thus the signal power in main lobes can be expressed as

$$\eta_m = \eta \times 81.06\,\% \quad (5.8)$$

As the application of the special case of GCE-BOC modulation for four signals on BeiDou B2 band is discussed in detail in [7], we will choose the multiplexing problem on BeiDou B1 band as an example to illustrate the effectiveness of GCE-BOC modulation in solving the dual-frequency multiplexing problem.

5.3 Application for B1 Band

5.3.1 Multiplexing Model of BeiDou B1 Band

The baseline of BeiDou B1 signals contains a traditional BPSK(2) signal at 1561.098 MHz and MBOC(6,1,1/11) signals and BOC(14,2) modulated Authorized Service (AS) signals at 1575.42 MHz [9]. BeiDou baseline options use MBOC(6,1,1/11) as global B1 Open Service (OS) signals, which are a mixture of BOC(1,1) and BOC(6,1) with a power ratio of 10:1. MBOC modulation has three different implementations: Composite BOC (CBOC), Time Multiplexed BOC (TMBOC) and Quadrature Multiplexed BOC modulations (QMBOC). CBOC modulation linearly combines BOC(1,1) and BOC(6,1) sub-carriers, and the waveform has four different levels, which leads to greater combining difficulty with other signals. In this paper TMBOC and QMBOC are chosen as the candidates for the BeiDou B1 signal. With different implementations of MBOC(6,1,1/11), different multiplexing tragedies will be adopted.

Summarizing the multiplexing problem on BeiDou B1 band, there might exist two multiplexing schemes. In the first scheme, TMBOC is chosen as the implementation of MBOC modulation, and there are five signals, as shown in Table 5.1, to be multiplexed.

The pilot and data channels of BOC(14,2) are realized by time division data multiplexing (TDDM), thus the waveform has only two levels, and there are only four signals to be multiplexed. B1I signal is located on the lower sideband, and B1A and B1C signals are located on the upper sideband. Thus the multiplexing problem on BeiDou B1 band is how to constant envelope transmit an asymmetric dual-frequency signal.

In the second scheme, QMBOC is chosen as the implementation of MBOC modulation, and there are six signals, as shown in Table 5.2, to be multiplexed.

The pilot and data channels of BOC(14,2) are realized by time division data multiplexing (TDDM), thus the waveform has only two levels, and there are five signals to be multiplexed. B1I signal is located on the lower sideband, and B1A and B1C signals are located on the upper sideband. Thus the multiplexing problem on BeiDou B1 band is how to constant envelope transmit an asymmetric dual-frequency signal.

The Interplex/CASM technology, a particular phase modulation combining multiple signals into a phase modulated composite signal, was preferred by GPS and Galileo systems because it provides good power efficiencies. Thus the Interplex/CASM modulation is chosen as the method to multiplexing the signals on each sideband into a constant envelope signal.

Table 5.1 Signals need to be multiplexing in BeiDou B1 band

Signal	Frequency (MHz)	Modulation	Service
B1I	1561.098	BPSK(2)	OS
B1Cp	1575.42	TMBOC(6,1,4/33)	OS
B1Cd	1575.42	BOC(1,1)	OS
B1Ap	1575.42	TDDM-BOC(14,2)	AS
B1Ad	1575.42		AS

Table 5.2 Signals need to be multiplexing in BeiDou B1 band

Signal	Frequency (MHz)	Modulation	Service
B1I	1561.098	BPSK(2)	OS
B1Cp	1575.42	BOC(1,1)	OS
		BOC(6,1)	OS
B1Cd	1575.42	BOC(1,1)	OS
B1Ap	1575.42	TDDM-BOC(14,2)	AS
B1Ad	1575.42		AS

5.3.2 The First Multiplexing Scheme with GCE-BOC Modulation

The four signals that need to be multiplexed are B1I signal, time-multiplexed B1A signal, B1Cp signal and B1Cd signal. We denote $s_1(t)$ as B1I signal, $s_2(t)$ as B1A signal, $s_3(t)$ and $s_4(t)$ as B1Cp signal and B1Cd signal respectively. The power constraints between $s_3(t)$ and $s_4(t)$ are set as the ratio of 3:1 as the GPS L1C signal, and the three signals are assumed as having equal power. Thus the power ratios between the four signals are 2:4:3:1.

The signals on the upper sideband modulated as a constant envelope signal by the CASM modulation by the same method as above can be expressed as

$$\begin{aligned} s_{up}(t) = & \left(\sqrt{P_I} s_3(t)\cos(m) - \sqrt{P_Q} s_4(t)\sin(m)\right) \\ & + j\left(\sqrt{P_Q} s_2(t)\cos(m) + \sqrt{P_I} s_2(t) s_3(t) s_4(t)\sin(m)\right) \end{aligned} \tag{5.9}$$

where P_I and P_Q are powers of in-phase and quadrature-phase channels, m is the coefficient that decides the power constraint between the signals, which can be defined as

$$m = \tan^{-1}\sqrt{\frac{P_{s_4}}{P_{s_2}}} \tag{5.10}$$

where the power of $s_2(t)$ and $s_4(t)$ are P_{s_2} and P_{s_4}.

Consequently, the constant envelope baseband signal acquired by GCE-BOC modulation can be expressed as

$$s(t) = \alpha_1 \operatorname{sgn}[\sin(2\pi f_{sc} t + \varphi_1)] + j\alpha_2 \operatorname{sgn}[\sin(2\pi f_{sc} t + \varphi_2)] \tag{5.11}$$

where

$$\begin{cases} \alpha_1 = \sqrt{\begin{aligned} & \left(\sqrt{P_{s_1}} s_1(t) + \left(\sqrt{P_Q} s_2(t)\cos(m) + \sqrt{P_I} s_2(t) s_3(t) s_4(t)\sin(m)\right)\right)^2 \\ & + \left(\sqrt{P_I} s_3(t)\cos(m) - \sqrt{P_Q} s_4(t)\sin(m)\right)^2 \end{aligned}} \\ \alpha_2 = -\sqrt{\begin{aligned} & \left(\sqrt{P_{s_1}} s_1(t) - \left(\sqrt{P_Q} s_2(t)\cos(m) + \sqrt{P_I} s_2(t) s_3(t) s_4(t)\sin(m)\right)\right)^2 \\ & + \left(\sqrt{P_I} s_3(t)\cos(m) + \sqrt{P_Q} s_4(t)\sin(m)\right)^2 \end{aligned}} \end{cases}$$

$$\begin{cases} \varphi_1 = \operatorname{atan2}\left[\dfrac{\sqrt{P_{s_1}} s_1(t) + \left(\sqrt{P_Q} s_2(t)\cos(m) + \sqrt{P_I} s_2(t) s_3(t) s_4(t)\sin(m)\right)}{\sqrt{P_I} s_3(t)\cos(m) - \sqrt{P_Q} s_4(t)\sin(m)}\right] \\ \varphi_2 = -\operatorname{atan2}\left[\dfrac{\sqrt{P_I} s_3(t)\cos(m) + \sqrt{P_Q} s_4(t)\sin(m)}{\sqrt{P_{s_1}} s_1(t) - \left(\sqrt{P_Q} s_2(t)\cos(m) + \sqrt{P_I} s_2(t) s_3(t) s_4(t)\sin(m)\right)}\right] \end{cases} \tag{5.12}$$

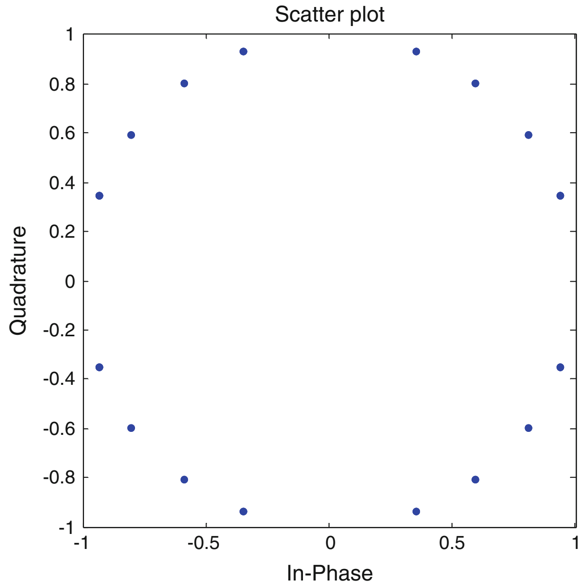

Fig. 5.1 Constellation of GCE-BOC$_{(1,3)}$

The constellation of GCE-BOC$_{(1,3)}$ modulation used in the first multiplexing scheme is shown in Fig. 5.1.

It is required that the multiplexing technology brings no obvious influence on signals receiving separately, which means that constant envelope multiplexing ought to be transparent to receivers. Users do not need to know which multiplexing technology is used, and only need to generate the replica of the desired component.

The power loss can be expressed as

$$\eta = \sum_{i=1}^{4} |R_i|^2 = \left| \frac{1}{T} \int_T \overline{s(t) s_i(t) e^{j2\pi f_{sc} t} dt} \right|^2 + \sum_{i=1}^{3} \left| \frac{1}{T} \int_T \overline{s(t) s_i(t) e^{-j2\pi f_{sc} t} dt} \right|^2 \quad (5.13)$$

where R_i is the average output of the correlator for $s_i(t)$.

The power loss calculated according to (5.13) is about 1.2496 dB. As the fundamental harmonic efficiency for square wave subcarrier is 0.8106, the efficiency of the desired signal power in main lobes is about 92.52 %.

5.3.3 *The Second Multiplexing Scheme with GCE-BOC Modulation*

The five signals that need to be multiplexed are B1I signal, time-multiplexed B1A signal, B1Cp signal and B1Cd signal. We denote $s_1(t)$ as B1I signal, $s_2(t)$ as B1A signal, $s_3(t)$ and $s_4(t)$ as BOC(6,1) and BOC(1,1) signals in quadrature respectively, which compose B1Cp signal, and $s_5(t)$ as B1Cd signal. The power constraints between B1Cp signal and B1Cd signal are set as the ratio of 3:1 as the GPS L1C signal, and the three signals are assumed as having equal power. Thus the power ratios between the five signals are 22:44:4:29:11.

Consequently, the constant envelope baseband signal acquired by GCE-BOC modulation can be expressed as

$$s(t) = \alpha_1 \operatorname{sgn}[\sin(2\pi f_{sc}t + \varphi_1)] + j\alpha_2 \operatorname{sgn}[\sin(2\pi f_{sc}t + \varphi_2)] \tag{5.14}$$

where

$$\begin{cases} \alpha_1 = \sqrt{\left(\sqrt{P_{s_1}}s_1(t) + \tilde{s}_1(t)\right)^2 + (\tilde{s}_2(t))^2} \\ \alpha_2 = -\sqrt{\left(\sqrt{P_{s_1}}s_1(t) - \tilde{s}_1(t)\right)^2 + (\tilde{s}_2(t))^2} \\ \varphi_1 = \arctan[\tilde{s}_1(t), \tilde{s}_2(t)] \\ \varphi_2 = -\arctan[\tilde{s}_2(t), \tilde{s}_1(t)] \end{cases}$$
$$\begin{cases} \tilde{s}_1(t) = \sqrt{P_{s_2}}s_2(t) - \sqrt{P_{s_3}}s_3(t) - \sqrt{\frac{P_{s_3}P_{s_5}}{P_{s_4}}}s_3(t)s_4(t)s_5(t) - \sqrt{\frac{P_{s_2}P_{s_5}}{P_{s_4}}}s_2(t)s_4(t)s_5(t) \\ \tilde{s}_2(t) = \sqrt{P_{s_4}}s_4(t) + \sqrt{P_{s_5}}s_5(t) + \sqrt{\frac{P_{s_3}P_{s_4}}{P_{s_2}}}s_2(t)s_3(t)s_4(t) - \sqrt{\frac{P_{s_3}P_{s_5}}{P_{s_2}}}s_2(t)s_3(t)s_5(t) \end{cases} \tag{5.15}$$

The constellation of GCE-BOC$_{(1,4)}$ modulation used in the second multiplexing scheme is shown in Fig. 5.2.

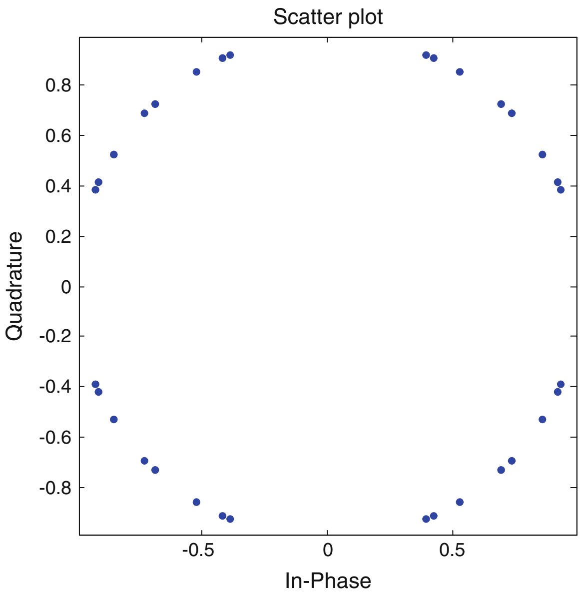

Fig. 5.2 Constellation of GCE-BOC$_{(1,4)}$

The power loss calculated according to (5.13) is about 1.6987 dB. As the fundamental harmonic efficiency for square wave subcarrier is 0.8106, the efficiency of the desired signal power in main lobes is about 83.43 %.

5.4 Conclusions

In order to solve the problem of multiplexing arbitrary number of signals on two sidebands into a signal with constant envelope, we present a generalized dual-frequency constant envelope modulation named GCE-BOC modulation. The modulation can be regarded as the extended form of Alt-BOC and ACE-BOC modulations. The application of GCE-BOC modulation on BeiDou B1 band is chosen as an example to illustrate the effectiveness of GCE-BOC modulation in solving the dual-frequency multiplexing problem. The generalized dual-frequency constant envelope modulation proposed not only gives some suggestions to BeiDou signal designs, but also provides a solution to dual-frequency constant envelope multiplexing problem for worldwide GNSS.

Acknowledgments The authors are thankful to Professor Kou Yanhong for her valuable remarks and suggestions.

References

1. Avila-Rodriguez JA (2008) On generalized signal waveforms for satellite navigation. University FAF Munich, Munich
2. Dafesh PA, Nguyen TM (1999) Coherent adaptive subcarrier modulation (CASM) for GPS modernization. In: Proceedings of the 12th national technical meeting of the institute of navigation, San Diego, CA, 25–27 Jan, pp 649–660
3. Butman S, Timor U (1972) Interplex-an efficient multichannel PSK/PM telemetry system. IEEE Trans Commun 20(3):415–419
4. Dafesh PA, Cahn CR (2009) Phase-optimized constant-envelope transmission (POCET) modulation method for GNSS signals. In: Proceedings of the 22nd international technical meeting of the satellite division of the institute of navigation, Savannah, GA, 22–25 Sept, pp 2860–2866
5. Lestarquit L, Artaud G, Issler J (2008) AltBOC for dummies or everything you always wanted to know about AltBOC. In: Proceedings of the 21st international technical meeting of the satellite division of the institute of navigation, Savannah, GA, 16–19 Sept, pp 961–970
6. Yao Z, Lu M (2013) ACED multiplexing and its application on BeiDou B2 band. In: Proceeding of 4th China satellite navigation conference, Wuhan, China
7. Dafesh PA, Cahn CR (2011) Application of POCET method to combine GNSS signals at different carrier frequencies. In: Proceedings of the international technical meeting of the institute of navigation, San Diego, CA, 24–26 Jan, pp 1201–1206
8. Kharisov V, Povalyaev A (2011) Optimal aligning of GNSS navigation signals sum. In: Proceedings of the 24th international technical meeting of the satellite division of the institute of navigation. Portland, Oregon, pp 3141–3155
9. Zhang K, Zhou H, Wang F (2011) Multiplexing performance assessment of POCET method for compass B1/B3 signals. J Navig 64:41–54